NOTCH TOUGHNESS REQUIREMENTS FOR WELDED PLATE, AND A PROPOSED TEST

Ronald Anthony Marcolini

NOTCH TOUGHNESS REQUIREMENTS FOR WELDED PLATE, AND A PROPOSED TEST

by

RONALD ANTHONY MARCOLINI
Lieutenant, United States Coast Guard

S. B. UNITED STATES COAST GUARD ACADEMY
1970

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREE OF OCEAN ENGINEER AND THE

DEGREE OF MASTER OF

NOTCH TOUGHNESS REQUIREMENTS FOR WELDED PLATE, AND A PROPOSED TEST

by

RONALD ANTHONY MARCOLINI

Submitted to the Department of Ocean Engineering and the Department of Mechanical Engineering on 9 May 1975, in partial fulfillment for the degree of Ocean Engineer and the degree of Master of Science in Mechanical Engineering.

ABSTRACT

Regulations of the U.S. Coast Guard (and some classification societies) and U.S. Navy are presented in detail and contrasted. Attention is drawn to the requirement for a minimum value of Charpy V-notch toughness in the HAZ. Is this too severe? There is some evidence to suggest that it might be, but there are many factors that must be addressed, and there is much uncertainty regarding them.

Some implications of notch toughness evaluation in weldments are the loading rate encountered, the three types of heat affected zones (HAZ), and the physical nature and orientation of HAZ cracks. The effects of these on weldment notch toughness tests are discussed.

Tensile tests were conducted on fatigue-cracked test strips cut from welded steel plate. While Charpy V-notch tests showed a HAZ with lower notch toughness than base metal, the results of the strip tests showed that the HAZ performed the same as the base metal. It was also found that the presence of two opposed notches had the detrimental effect of raising transition temperature by 80 degrees (F).

Thesis Supervisor: Frank A. McClintock

Title: Professor of Mechanical Engineering

Thesis Supervisor: Koichi Masubuchi

Title: Professor of Ocean Engineering

ACKNOWLEGEMENTS

I will be forever indebted to my wife, Pat, and my son, Tim, for their patience, understanding, and moral support during this worthwhile undertaking.

It has been of tremendous value to me to work with such a gifted and conscientious person as Professor Frank A. McClintock. He made this an extremely rewarding and enlightening experience for me.

The cooperation of Ken Rollins and associates at the Army Mechanics and Materials Research Center is greatly appreciated. Their friendly help made all the experimental results possible. I am also grateful to Professor Koichi Masubuchi for his advice and financial support.

Others to whom gratitude is extended are as follows: Ken Griffiths, Walter Hahn, Wayne Hawkins, Frank Zaverl, Jim Hannoosh and June McClean. Finally, I thank Karen Aykanian and Paul Hagstrom for the excellent typing job.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

LIST OF TABLES

CHAPTER I

INTRODUCTION

Ever since the catastrophic brittle fractures in many Liberty ships during and after World War II, the importance of adequate notch toughness in weldments has been continually emphasized. This emphasis is evident from the present existence of numerous standards and requirements for notch toughness, the aim of which is to minimize the occurrence of brittle fracture in actual service structures.

APPROACHES TO NOTCH TOUGHNESS REQUIREMENTS

Standards and requirements for notch toughness of weldments generally take more than one approach. For instance, direct notch toughness can be measured by means of a test on the metal, with some form of acceptance criterion established for that particular test. This is the primary approach which is taken. A second approach is that the chemistry of the base plate and weld electrode can be restricted by the standard, and/or the mill practice specified. A third approach is to carefully specify certain parameters in the welding process such as heat input, preheat, and post-weld heat treatment in order to avoid brittleness. Yet another method of protecting against fracture of a weldment is to perform non-destructive tests in order to detect defects. In practice, these approaches are combined.

All of these methods of attack zero in on one basic facet, however: notch toughness. The whole point of specifying chemical composition and/or mill practice is to achieve a certain level of notch toughness. Weld parameter control is exercised for the same reason. And the critical size of a defect is dependent directly on the amount of notch toughness of the material in its vicinity. Therefore, the aim of performing notch toughness tests is seemingly self-evident.

LACK OF BASIS FOR REQUIREMENTS

However, those notch toughness tests for weldments that are currently called for by the standards and requirements suffer from a lack of solid theoretical understanding of fracture processes in weldments (because of the continuing inadequate state of knowledge on the subject). So, without a solid theoretical basis, toughness tests have evolved from experience and are evaluated on the basis of experience. That is, if no service failures resulted from implementing a particular test procedure, then it is considered satisfactory. Also, acceptance criteria, such as minimum allowable Charpy V-notch energies, for example, for a new steel are decided upon based on past experience with a similar steel.

Such an approach leads to overkill (whereby the stan-

dards are too conservative) and inconsistency. Overkill is obvious because a standard which has resulted in no failures most likely gives a margin of safety that is much larger than necessary. The existence of overkill may have been the reason for some interesting inconsistencies. One of these is the allowance by some ship classification societies of lower notch toughness for submerged arc deposited weld metal versus covered electrode weld metal [1]. Another example is in the use of HY-80 by the U. S. Navy for submarine hulls. Charpy V-notch energy values for HY-80 base plate are much more stringent than those for the weld metal electrodes. Also, no consideration is given to specifically how much loss of Charpy V-notch toughness occurs in the heat affected zone (HAZ) in HY-80 weldments. As noted in reference [1], "The low notch toughness requirements have been set in some cases because weld metals with higher notch toughness are not available at the present time, not because notch toughness is less important in the weld metal than in the base metal."

HAZ TOUGHNESS REQUIREMENT

Considering this, one's attention is drawn to the present standards that require the same Charpy V-notch toughness in the heat affected zone (HAZ) and weld metal as for the base plate. Are these examples of overkill?

Before attempting to answer this question, it is felt that details of ship weldment standards of some leading organizations should be presented. This will give perspective to later discussions of notch toughness evaluation of weldments and the subsequent experimental test procedure.

CHAPTER II

DETAILS OF SOME WELDMENT NOTCH TOUGHNESS STANDARDS FOR SHIPS

II.A. U. S. COAST GUARD

II.A.1. GENERAL

Strict requirements by the Coast Guard for the notch toughness of weldments is limited almost entirely to service temperatures below 0°F . The actual requirements are spelled out in part 54 of the publication entitled CG-115 [2] or Marine Engineering Regulations, Subchapter F. Subparts 54.05 and 54.25 are of interest here. They deal with toughness tests and steel types respectively. Different steels may be required to pass different toughness tests, and this in turn affects which test will be called for in weldment testing. There are two types of weldment tests that are used. First, the weld procedure qualification toughness tests must be passed before any given weld procedure can be used on a ship. Then, as a means of testing the actual welds on a ship, weld production tests are also required. The paragraphs to follow will elaborate further.

II.A.2. TOUGHNESS TESTS

There are two types of toughness tests that are required most commonly for weldments (and base plate). These are the Charpy V-notch impact test (Appendix A.1) and

the Drop Weight Test (DWT) (Appendix A.2). The acceptance criterion for the Charpy V-notch test is usually a minimum impact energy at a certain minimum temperature. The acceptance criterion for the DWT is a no-break performance at a specified temperature; this ensures that the particular temperature is greater than nil ductility transition (NDT) temperature.

There are provisions for special tests in the Coast Guard rules also. The Explosion Bulge Test (EBT) (Appendix A.3) is one example [3]. Another test that is becoming more widely used is the Dynamic Tear Test (DTT) (Appendix A.4) which is already an established test for Navy use. Also, it is possible that other tests, if given CG approval, may be utilized.

II.A.3. STEEL TYPES

The reason for detailing the categories of steels in the CG requirements is that the type of toughness test called for depends on the type of steel being welded. There are four categories of steels listed in CG-115*.

FERRITIC STEELS (turn to Appendix B.1)

These steels are described in the appendix and comprise the biggest category. There has been much

*These same categories are used in the ASME Boiler and Pressure Vessel Code, Section VIII.

experience with them; in fact, it is for them that the firmest Charpy V-notch acceptance criteria have been established. The impact energy for ferritic steels at service temperatures between -70°F and 0°F is 30 ft-lbs minimum for full-sized Charpy specimens. For ferritic steels below -70°F (mainly A-203 Ni steels), the minimum impact energy is 25 ft-lbs for a full-sized specimen.

HIGH ALLOY STEELS (turn to Appendix B.2)

These are predominantly austenitic stainless steels. A wide temperature range is covered. The notch toughness requirements for these materials generally consist of DWT's instead of Charpy tests.

FERRITIC STEELS WITH PROPERTIES ENHANCED BY HEAT TREATMENT (turn to Appendix B.3)

As stated in the appendix, Charpy lateral expansion rather than impact energy is used as the acceptance criteria. This is very similar to the corresponding category in the ASME Code (UHT-5(c), UHT-6(a), (4) and (5)).

QUENCHED AND TEMPERED STEELS (turn to Appendix B.4)

Because the notch toughness of welded quenched and tempered steels can be controlled significantly by controlling the welding heat input (and other welding parameters), notch toughness tests are not always required for them [4]. However, when testing is called for, the EBT [3] is used for these steels as noted in the appendix.

<u>HULL STEELS</u> (turn to Appendix B.5)

The above steels, which are listed in CG-115, are prescribed for use in pressure vessels and primary and secondary barriers. But the notch toughness test requirements listed in this publication are applicable to some <u>hull</u> steel applications [5] also, as detailed in Appendix B.5. Generally speaking, for service temperatures below 0°F, notch toughness testing (Charpy) is required for hull steel weldments.

II.A.4. <u>WELDMENT TESTS</u>

As stated above, weldment toughness testing is of two types, welding procedure qualification tests and production weldment tests.

<u>PROCEDURE QUALIFICATION TEST</u>

CG-115 calls for the same toughness test for weld procedure qualification as that required for the base metal. Plate, for which Charpy testing is required and minimum energy values specified, shall also have Charpy tests conducted for approving a weld procedure where the given material is to be used. A most important facet of this requirement is the stipulation to test not only the weld metal, but to traverse the HAZ also (see Fig. II-1). Charpy specimens are required with the notch centered at the following locations: weld fusion line, 1 mm from weld fusion line,

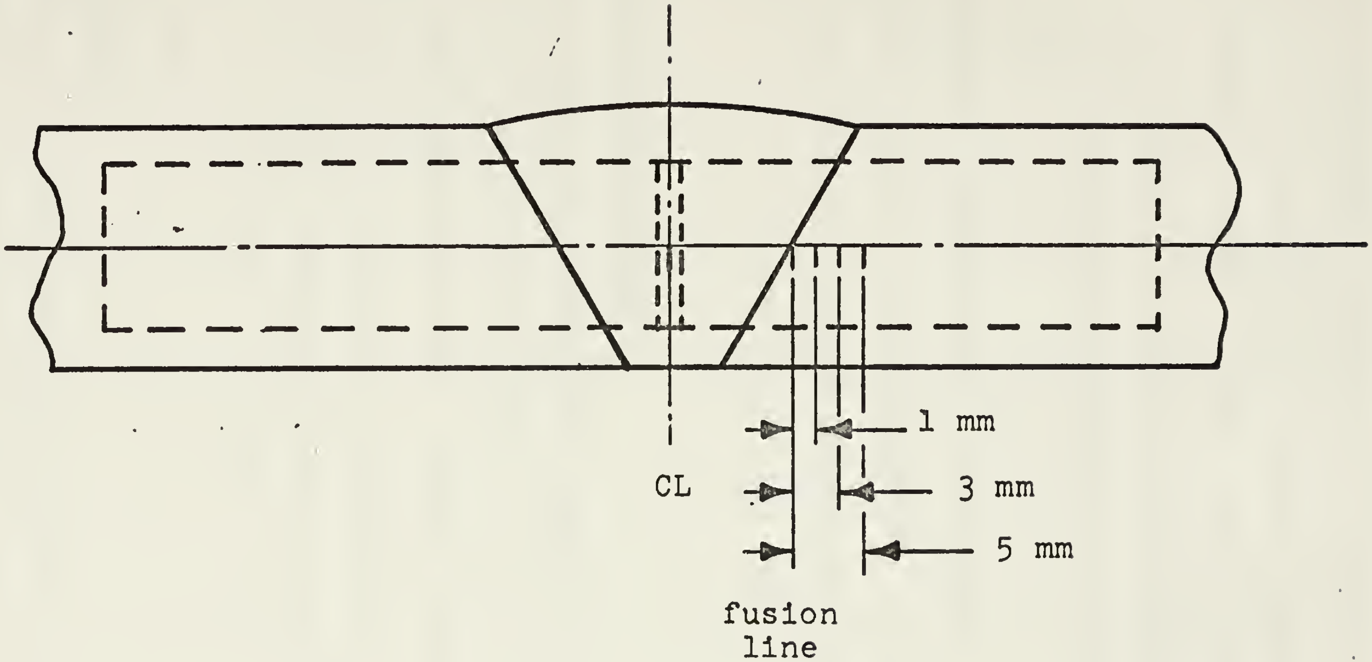

Figure II-1. Notch locations for Charpy V-notch specimens in CG weld procedure qualification toughness tests.

3 mm from weld fusion line, and 5 mm from weld fusion line. This requirement reflects the present Coast Guard position that assessment of the HAZ is very important. It is partly because of this feeling that the DWT is discouraged as a weld procedure qualification toughness test (because the DWT is inherently incapable of examining the HAZ accurately [6]).

It should be stated that the DWT may be used for procedure qualification in rare instances. It is routine to use it for austenitic stainless steels and their weldments (this results in no assessment of the HAZ for most of these steels).

PRODUCTION TESTING

Specimens for production toughness tests are obtained from run-off tabs attached at the ends of actual ship-board weld butts or seams. Charpy specimens are to be cut exactly as for procedure qualification tests except that location of HAZ specimens shall be restricted only to that location which showed the lowest energy values in the procedure tests.

RETESTS

Given the high degree of scatter in Charpy V-notch impact energies, certain amounts of scatter are allowed if more test data can achieve the desired average. Generally, if a set of procedure qualification Charpy tests fail, even

after following the retest procedure in Subpart 54.05, the procedure is not approved by the Coast Guard. However, if the procedure passes the Charpy tests, but the production Charpies fail (even with proper retesting), there is still a means for approving the ship-board weldment. This can be done by using the drop weight test, as per Subpart 54.05 of CG-115. The intent of this procedure is to conduct one last test before deciding to rip out a weld on a ship. If the DWT passes, then the weld is allowed to remain [7].

II.A.5 ALTERNATE TOUGHNESS TESTS FOR WELDMENTS

From the preceding information, it can be seen that there is a definite preference for the Charpy test as a means of qualifying weldments for notch toughness in CG regulations. But there are provisions to use alternate tests and/or acceptance criteria. It will be informative to investigate these.

First of all, the stated Charpy energy values (which apply only to ferritic steels), although the most common acceptance criteria, may be replaced by other values with special approval. Approval can be obtained from the Coast Guard if there is sufficient data that shows suitable correlations of the DWT and Charpy test for the material. The actual values depend on the specific correlation. These new values would then also be required for weldment

qualification.

The explosion bulge test (EBT) is one alternate toughness test method, but is restricted to higher strength quenched and tempered steels. Since CG-115 was written, this test has become almost standard for these steels [6] (each case is considered individually, however).

An up-and-coming test is the dynamic tear test (DTT), developed at the Naval Research Laboratory. It is receiving much attention at Coast Guard Headquarters, where the feeling is that it should arrive soon as an established test*. A particular failure that has had a major impact on CG thinking is the HAZ fracture of barge IOS 3301 [8] in New York in 1972. The DTT curves for steel from this barge showed good correlation with the actual failure, much better than Charpy curves [7]. Thus it can be expected that for certain cases, the DTT will be utilized in Coast Guard regulation procedures in the near future [7].

The drop weight test, for CG use, has undergone a significant evolution, based on experience. It is generally considered to be a foolproof method of determining NDT temperature, and it has thus served as a basis for setting

---

*The DTT is already in the ASTM grey pages, which means it will become a firm part of the standards in three years if there is satisfactory experience with it in the meantime [7].

up Charpy acceptance criteria. It is even called for by CG-115 to replace the Charpy in some specially considered cases. But actual use of the DWT instead of the Charpy test has been rare, and has been restricted to base metal only when it has been used. (One exception is austenitic stainless steels where the DWT is called for in weld procedure qualification as well as base plate acceptance.) In fact, less and less emphasis on the DWT can be expected in future CG regulation cases. The reason for this is because the test is felt to be more liberal than the Charpy test [9]. This conclusion has been drawn from observing many correlations between the two. The other factor which discourages use of the DWT for weldments is that it cannot evaluate the HAZ properly [6].

From the above discussions of alternate toughness tests to the Charpy V-notch test, it should be clear that the Coast Guard gives very much attention to each individual case, especially if it is the least bit out of the ordinary. The regulation process is not simply a matter of following the book; it requires analysis by many persons on the Coast Guard side, who in turn are guided by the experiences of all of industry and of technical organizations (such as ASTM, ASME, AWS, etc. [6, 7, 9].

II.B. OTHER CLASSIFICATION SOCIETIES

II.B.1. AMERICAN BUREAU OF SHIPPING

The ABS is similar to the Coast Guard regarding its weld procedure qualification of low temperature (< 0°F) materials. Charpy V-notch impact testing is required exactly as in CG-115, i.e. specimens must be taken so as to traverse the HAZ and weld at the weld metal, fusion line, and 1 mm , 3 mm , and 5 mm from the fusion line. Also, the minimum Charpy energies must equal those of the base metal [10].

It is not surprising that the ABS and USCG worked very closely [9] in coming up with the low temperature (< 0°F) regulations when one compares the two. The only steels for which specific Charpy energies were given in the CG regulations were ferritic steels. For temperatures between 0°F and -70°F the requirements for Charpy energies, and also chemical properties, tensile properties, manufacturing process, and heat treatment are exactly the same in the ABS rules. (There is a specific paragraph allowing for different energies for -70°F < T < 0°F to be considered when there is suitable correlating data between Charpy tests and DWT's.) This is also the case, for the most part, as in CG-115, for steels at temperatures below -70°F (but above -320°F). The Coast Guard calls for specific Charpy

energies for specific steels (i.e. Ni steels, Subsection II.A.3; Appendix B.1) in this case. The ABS does so also (including the <u>same</u> values of Charpy energy), but it also offers the option of using <u>lateral expansion</u> of a Charpy specimen instead of impact energy as an acceptance criterion. This is to be contrasted with the use of lateral expansion as the <u>only</u> criterion for <u>heat treated</u> ferritic steels in CG-115 (Subsection II.A.3; Appendix B.3).

An important point is that the ABS and Coast Guard both feel that assessment of the HAZ is important and thus place emphasis on Charpy testing versus drop weight testing. The ABS has allowed the DWT for weld procedure qualification in addition to the Charpy test, however. And it is possible, although very unlikely, that the DWT could be used instead of the Charpy test for procedure qualification by ABS. But generally speaking, the Charpy test is preferred for acceptance of weldments [10, 11].

II.B.2. <u>DET NORSKE VERITAS</u> [12]

This Scandinavian classification society has weldment toughness rules that are more stringent for low temperature service versus normal temperatures, just as the U. S. Coast Guard and the American Bureau of Shipping. Specifically, for tanks (low temperature), weld procedures

shall be qualified for notch toughness by Charpy V-notch impact tests. Test specimens are to be taken in the centerline of the weld metal, at the fusion line, 3 mm from the fusion line, 5 mm from the fusion line, and 7 mm from the fusion line. All of these specimens are required to meet the same minimum energy requirements as for the base metal, just as in the CG rules. Of the four locations in the fusion line or HAZ, that which gives the lowest energy reading in the weld procedure qualification test above shall be Charpy-tested again when the workmanship (equivalent to production tests) test welds are evaluated for notch toughness. (For vessels that are not liquefied gas types, production impact tests are only required for the fusion line and not the HAZ [12]).

Two very important observations are: (1) for the HAZ, no tests are required at 1 mm from the fusion line; (2) impact testing is required 7 mm away [12]. It would seem that for the former case there might be neglect of a significant portion of the HAZ, namely the coarse-grained zone. It is in this area that low notch toughness could be obtained for some welding processes (more will be discussed on this later on). On the other hand, by requiring impact tests as far away as 7 mm , it appears that there is a much greater chance of hitting the thermally strained zone (which will be mentioned later), an area that many

believe will not degrade a weldment's performance even if it has low values of Charpy impact energy. (There are important implications concerning this area; they will be dealt with later on.)

A provision that is very similar to CG practice is that if these production test Charpy energies do not meet the requirements, then there is still a possibility for special approval of the weldment by use of the drop weight test. This policy closely parallels that of the CG on production weld approval, as was mentioned earlier [12].

II.B.3. IMCO* GAS SHIP CODE [13]

The IMCO Gas Ship Code offers some interesting observations. It was developed by members of many countries and thus represents the first international effort for cold temperature applications. It is expected to go into effect in the near future.

This code prescribes weldment procedure qualification in much the same manner as the U. S. Coast Guard and the American Bureau of Shipping. The main facet of this similarity is that HAZ, fusion line, and weld metal Charpy V-notch impact tests are required in exactly the same manner as the above named organizations. That is, HAZ tests are

*Intergovernmental Maritime Consultative Organization

prescribed for 1 mm , 3 mm , and 5 mm from the fusion line, just as before [6, 13].

The similarities noted have some important implications. By having many countries present to develop the code, there was the opportunity to "get the bugs out" of the previously written standards, if there were any bugs, in coming up with the new code. But the end result is very similar to what had already been used (at least in the U. S.), as far as notch toughness testing of weldments is concerned. One main reason for this is the major influence that the Coast Guard had in the code's development [6].

II.C. U. S. NAVY

II.C.1. GENERAL

Looking at the way the U. S. Navy qualifies weld procedures to avoid fracture offers some very interesting contrasts to what has been presented so far. Basically, the Navy takes a significant part in designing the particulars of a procedure through extensive research, including fracture evaluation. In addition, small specimen HAZ tests are not required. These are the two points of difference between the Navy and the other classification societies.

II.C.2. DETAILS

Weld procedure qualification for materials and electrodes with which there has been previous experience is more cut and dried. For these materials much information is available on optimum welding procedures, whether it comes from Navy publications or from industrial experience. The only real question of concern to the Navy is whether the fabricator can actually perform the procedure in a satisfactory manner (procedure qualification) [14]. A number of tests, both non-destructive and destructive, are used to show this. Those which assess fracture characteristics are the impact tests* (Appendix A.5). But impact tests are only required for a few cases, as noted in the appendix. However, any time impact testing is required, no HAZ specimens are called for. The reason is partly due to the favorable HAZ experience with these materials in the past. But for some cases, the Navy may have conducted preliminary (on the research level) explosion bulge testing (see Appendix A.3) and proved to itself that HAZ degradation was not a problem for the particular materials [14, 15].

For new materials, without significant previous experience, it is through similar preliminary evaluation (research and development) of not only fracture characteristics,

---

*except for quenched and tempered steels

but of all elements of welding (joint design, material forming, workmanship, heat input, pre-heat, etc.) that the detailed procedure can be written up and simply handed to the fabricator. Thus, even for a newer material which the fabricator may not have welded previously, there is very little uncertainty about the best way to do so. The Navy tells the fabricator the best way. The only question would again be whether or not he is capable of welding the material according to the Navy's requirements (procedure qualification). And, again, a number of destructive and non-destructive tests (as determined from the research and development with the material) would be called for, although some may be different than those for more familiar materials. Perfect examples of this procedure are the steels HY-80 and HY-100 [14, 16]. For fracture assessment of these, explosion bulge testing (Appendix A.3) is used [16]. Optimum welding procedures require strict heat control to achieve good notch toughness, as determined from Navy research and development [14]. This detailed information that the Navy provides on weld procedures is one factor in contrast with the Coast Guard requirements.

The other factor that makes Navy notch toughness requirements different is that no HAZ impact tests are required. The first reason for this is the evolution of the explosion bulge test as a good means for checking HAZ

degradation (see Appendix A.3) [14]. But, except for quenched and tempered steels (HY-80, HY-100 , HY-130) there just has not been any problem with HAZ degradation in the Navy [14]. A probable reason for this is that the operating temperatures of Naval ships are well above NDT temperature, so that even if there was slight degradation, it would not make much difference. The other reason for not requiring HAZ impact tests is that the explosion bulge test very adequately evaluates quenched and tempered steel weldments for the Navy's purposes (i.e. explosive loading in war time is indeed what the Navy wants to design ships against) [14].

II.D. DISCUSSION

II.D.1. GENERAL

Having studied the previous different approaches to notch toughness requirements, the sharpest contrast is between the Navy's method and the others. This contrast will be discussed and analyzed here. It will be limited to comparing the Navy requirements with the Coast Guard requirements only (due to the similarity of the classification societies to the latter).

II.D.2. POINTS OF DIFFERENCE BETWEEN NAVY AND COAST GUARD REQUIREMENTS

To understand these differences requires looking at different aspects, from ordering the steel to checking the final weld in a ship. After doing so, it will then be clearer why there is such a contrast between notch toughness requirements. There are four levels of regulation that should be studied: (1) choosing the steel; (2) determining a welding procedure; (3) testing the fabricator's capabilities regarding the welding procedure; (4) controlling and evaluating the service weldment.

These are depicted in Table II-1. This table gives valuable information on how these steps are carried out in the two different cases. Comparison is made between Navy regulation of a material in a higher risk application (or possibly a new material) like HY-80 and Coast Guard regulation of a similar situation (lower temperature steels (Subsection II.A.3; Appendix B)).

For level (1) the Navy specifies the exact steel at the design stage of the ship without any input from the fabricator (unless familiar materials were being used). On the other hand, having to fulfil Coast Guard requirements, the fabricator picks a low temperature steel (Subsection II.A.3; Appendix B) from those listed in CG-115 [2] (or

TABLE II-1

LEVELS OF REGULATION FOR NOTCH TOUGHNESS REQUIREMENTS

		NAVY (Q and T steels and new materials)	COAST GUARD (low temperature)
LEVEL 1:	Choosing Material for Construction	Navy does this	Fabricator does this
LEVEL 2:	Determining Welding Procedure	Navy does this (may include HAZ evaluation at R and D stage)	Fabricator does this
LEVEL 3:	Testing if Fabricator Can Qualify with the Weld Procedure	Fabricator must pass Navy tests	Fabricator must pass CG tests (include HAZ impact tests)
LEVEL 4:	Regulation of Welding during Construction	Pre-welding regulation: control pre-heat and heat input	Pre-welding regulation: no heat control
		Post-welding regulation: non-destructive testing	Post-welding regulation: non-destructive and also <u>production</u> testing

possibly gets special approval for an alternative).

For level (2) the Navy develops the proper welding procedure using certain tests [14]. These tests may include checking the HAZ by explosion bulge testing if HAZ degradation is possible; or, if it is not deemed significant, HAZ assessment would be stopped in the research and development stage (this was the case for some of the steels mentioned in Appendix A.5) [14]. The Coast Guard, however, has not developed any welding procedures; it requires the fabricator to do so. And it is at this point that the fabricator must look at the CG requirements in determining his weld procedure. Actually, he should be considering levels (1) and (2) together to ensure he will get a passing grade at level (3).

For level (3) the overall requirement for each case is the same: undergo official tests to prove to the Navy or Coast Guard that the fabricator is <u>capable</u> of producing a sound weld. But the tests for weld procedure qualification differ between the Navy and Coast Guard. Specifically, to evaluate the HAZ, the explosion bulge test is used for HY-80 weld procedure qualification, whereas Charpy specimens are called for in the HAZ of most of the low temperature steels (Subsection II.A.3; Appendix B). It is possible, however, to have a Navy steel with no HAZ requirement at all; the reason would be that HAZ degradation was proven to be no

problem for the specific procedure in the research and development stage [14].

For level (4) the objective is again the same for each case: ensure that the <u>service</u> weldment is proper. Coast Guard and Navy rules both rely on non-destructive testing as one means of doing this. But production tests are also required by the Coast Guard (Subsection II.A.4), while none are required by the Navy. However, for HY-80 and other quenched and tempered steels, strict heat control in welding is mandatory for optimum notch toughness - consequently, this is all the Navy requires.* However, in the cold steel (Subsection II.A.3; Appendix B) applications (which are generally not quenched and tempered steels) there is no point in controlling heat input. Therefore, the production test is needed (Subsection II.A.4) to indicate the notch toughness of the weldment.

It is clear at this point that the comparison of the Navy and Coast Guard standards has actually been a comparison of "apples and oranges" to an extent (comparing a quenched and tempered steel to non-quenched and tempered types). But it has nevertheless shown the different approaches taken, which is very important information. In

---

*CG does the same for commercial quenched and tempered steel applications.

summary, the Navy does much of the preliminary investigation (research and development) on a high risk/new material and its optimum welding procedure. It thus requires less homework for the fabricator.

II.D.3. CONCLUDING REMARKS

From a broad perspective, the fabricator is generally a little harder pressed when building a commercial ship versus a Navy ship. The reason is that he must do more homework on economically optimizing both his steel choice and welding procedure, while at the same time making sure he will pass Coast Guard requirements. For Naval construction, however, the fabricator does not have to choose the steel or determine the weld procedure; but he does have to prove to the Navy, in the design stage, that he can weld the material as specified by Navy publications. The fabricator is not responsible for steel quality, however, in building a Naval ship; the Navy usually places full responsibility with the steel supplier [14, 16].

An interesting question is, coupled with the previous paragraph, are the Coast Guard HAZ requirements unrealistic or overly tough as compared to the Naval practice with HY-80. This is a somewhat inappropriate comparison. First of all there is certainty about the factors causing low notch toughness in HY-80 weldments. But for the cold

(< 0°F) steel applications (Subsection II.A.3; Appendix B), which have wider variation, there is a lack of certainty about how the notch toughness of the HAZ as measured by Charpy tests affects the performance of the weldment. The Coast Guard and other classification societies have many inputs of opinion from the steel companies and committees of the ASTM and ASME, but there is general concurrence with this requirement, despite the uncertainty. In fact, because it cannot be proved that the requirement is inappropriate, the Maritime Administration has contracted the National Bureau of Standards to conduct a detailed study of low temperature use of materials (no information is expected for a few years) so that better information will become available [17]*.

Another important factor to consider is that industry itself, besides the Coast Guard, wants desperately to avoid a catastrophic failure (especially for hazardous substances like liquefied gases). Because they desire to avoid legal litagition, people in industry feel that the relatively minor economic benefits that would result from a less stringent HAZ toughness requirement are insignificant when the risks are taken into account [4].

---

*This non-routine study is to be contrasted with the routine research and development which goes into new Naval high risk material applications.

In summary, there is no unified opinion on exactly what should be appropriate HAZ notch toughness requirements for cold (Subsection II.A.3; Appendix B) steel applications [7]. Industry cannot afford to undertake extensive research and development (as the Navy does) prior to using a material for these high risk situations. Consequently, the uncertainty lingers. The next chapter will give some implications of notch toughness assessment of weldments in general and the HAZ in particular.

CHAPTER III

INFORMATION REGARDING NOTCH TOUGHNESS EVALUATION OF WELDMENTS

III.A. WELDMENTS IN GENERAL

III.A.1. SOME BACKGROUND INFORMATION

The importance of controlling notch toughness in weldments stems from the presence of embrittlement. The causes, though not well understood, include the state of stress, thermal and strain cycling, strain ageing, irradiation, exhaustion of ductility, and certain metallurgical content [18]. In depth studies are presently underway to comprehend not only the microstructural events which are caused by the above factors, but to understand basic microstructural behavior itself. On the other hand, there is work that simply assesses the end effects (e.g. change of transition temperature) of whatever brought about the embrittlement without addressing its cause; it is this end of the spectrum in which the structural designer operates and to which this study will be devoted. And it is for this purpose that various tests for notch toughness have been developed.

NOTCH TOUGHNESS TESTS FOR WELDMENTS

Besides the Charpy V-notch test, other small specimen tests that have become popular for analyzing notch toughness of weldments are the crack opening displacement [19] (COD) test (Appendix A.6), the K_{Ic} test, the drop weight test (Appendix A.2), the Lehigh test [1, 20, 21], the Kinzel test [1, 20, 21], and more recently the dynamic tear test (Appendix A.4) and the Niblink [22] test (Appendix A.7). All these tests provide transition temperature information, primarily (except K_{Ic} and possibly COD).

The main problem associated with these small specimen tests is that they cannot simulate the real, complex geometrical conditions that a crack encounters in an actual weldment. It is for this reason, mainly, that use of larger scale (i.e. those which include a weld and its surrounding material) tests, such as the explosion bulge test (Appendix A.3), the Wells wide plate tension test [1], the Delta test [23], and the deep notch test [24] has grown. Besides being too small to simulate an actual weldment, the small specimen tests have been shown to have other deficiencies (e.g. pinpointing a wrong transition temperature) so that correlations [1, 25] are being made more frequently; these correlations are either between the small-scale tests or between large and small-scale tests.

III.A.2. METHODS OF APPROACH

NAVAL RESEARCH LABORATORY (NRL)

The largest impact on methods of preventing fracture of structures has been from the Naval Research Laboratory under the leadership of W. S. Pellini. Although his concept of Fracture Safe Design does not specifically address weldments, it has been used very successfully in welded structures.

This idea involves not only the mechanical aspects (such as test methods) but also the metallurgical aspects; the two are considered together in detail [21]. Some valuable tools fcr NRL researchers have been "interpretive procedures" [21, 26] involving use of the Fracture Analysis Diagram (FAD) and the Ratio Analysis Diagram (RAD) [21,26]. Although fracture mechanics plays a role in these procedures (at the research end), the main thrust of Fracture Safe Design is to design where there is enough plasticity (large plastic zone) so that fracture mechanics does not actually apply. The idea is to get an on-the-safe-side design, even though it may not be quantitatively known how safe [26].

The most dangerous situation, according to NRL researchers, is the case of an existing sharp crack which can be easily propagated by low stress [21]. In order to

evaluate this condition, the arrest and transition temperature behavior of the structure must be duplicated in the mechanical test procedure used. The DWT* (Appendix A.2) and the EBT* (Appendix A.3) are two tests that have been used successfully for some time to assess dynamic fracture characteristics of steels. The DTT* (Appendix A.4) also measures the dynamic condition; it has the added advantage of giving quantitative (energy values) information. This test has been shown to offer much better correlation to structural performance than the Charpy V-notch test (to be discussed in Section III.A.3).

CORRELATIONS

Except for the Navy, general practice does not involve the research which NRL conducts. The main objective in design and construction is to have convenient and reliable means of determining the notch toughness of a structure, without conducting preliminary research. Small scale tests are generally used due to convenience (simple, economical, small amount of material, quick). But their reliability has come under increasing fire. Reasons for this decreased confidence involve their irrelevance to geometric conditions in an actual weld, their improper transition temperature determination, and the inapplica-

---
*Developed by NRL

bility of some (Charpy V-notch test, discussed in Subsection III.A.3) to a broad category of steels.

In order to increase the reliability of small scale tests, correlative studies [1, 21, 22, 25] involving larger-scale, full-size weldment tests have grown enormously. The expense of these large scale tests generally limits them to strictly research use, however. But they can help better characterize small specimen tests so that the latter can help in obtaining improved information about a service weldment.

INTERNATIONAL INSTITUTE OF WELDING

From a philosophical point of view, the IIW has held for a long time that the objective of attaining fracture resistance in a weldment consisted of controlling two aspects of fracture: initiation and propagation. Because of the very high probability of defects in the weld zone (i.e. weld metal or HAZ), the objective has been to design against fracture initiation from these defects [22]. But if a fracture did initiate, it generally propagated dynamically out of the weld zone into the base metal.*
Therefore, emphasis has been on fracture propagation resistance in the base metal where arrest of a running crack is

*Nibbering [22] has noted that these observations were for the wide plate tests and the Kihara deep notch test, both of which are large scale weldment tests; this deviation of the crack is attributed to residual stresses [22].

desired.

Looking at fracture resistance in the weld zone, and considering the desire to prevent fracture initiation there, a few different types of small specimen tests have been used. The COD [19] test (Appendix A.6) has established itself in IIW circles. The Charpy V-notch test has been and is still being used, although limitations do exist (to be discussed later in Subsection III.A.3). A third alternative that has gained popularity is the Niblink [22] test (Appendix A.7). These tests have all been used to measure tendency for fracture initiation.

DISCUSSION

Major issues in the use of these or any tests are: (1) should crack initiation or crack propagation be considered; (2) how does loading rate relate to (1)?

The rational approach to these issues is as follows. For structures that undergo slow loading, a notch toughness test which itself involves slow loading is appropriate to measure tendency for crack initiation. But for this same statically loaded structure with a running crack, dynamic crack propagation resistance is of concern. On the other hand, for structures which undergo dynamic or high strain rate loading, it is felt that a notch toughness test that itself involves fast loading is appropriate to prevent fracture initiation. For a running crack here, dynamic

propagation resistance is again important [21,22].

Propagation. In addition to the rational approach discussed above, other factors are very important. Specifically, the beneficial influence of residual stress (i.e. causing propagating cracks to deviate away from a brittle weld or HAZ into more ductile base metal) may not always exist. This would be the case for the following conditions [22]: (1) high heat input to the weld; (2) higher yield stress of the material; (3) higher working stress (could show up in plastic straining which eliminates residual stress); (4) stress relief. If any of these conditions prevail, a greater possibility of a crack propagating through the weld zone (weld metal or HAZ) exists. And if this happened, the previously held IIW design criteria of preventing crack initiation in the weld zone would not be appropriate. A better design criteria for weld zone material would obviously involve a test that measures propagation-arresting capability. This is an important consideration, even in statically-loaded structures where a fast running crack is dynamic in nature.

NDT temperature. To combat fracture propagation, it is believed that material must be above the nil-ductility transition (NDT) temperature [21, 22], so that there is capability of crack arrest. The drop weight test is the accepted means for determining NDT temperature. But a

serious drawback in its use with weldments is that the brittle starter weld bead tends to heat treat and thus improve the material of the weld zone directly beneath it [22].

With the above considerations in mind, it will be valuable to look at two proposals to evaluate and control weldment notch toughness that are on opposite ends of the spectrum.

A novel proposal. Some recent work [22] has suggested one possible alternative approach in accounting for propagation and NDT temperature. This involves consideration of fatigue (due to the cyclic loading which most structures undergo). Structural fatigue is generally low cycle - higher stress. It involves a running crack. In actual experimental work, cited in reference [22], fatigue cracks were propagated through the HAZ of a high heat imput weld. Observations from this work have shown some significant benefits to this type of testing. First, the crack has the opportunity to follow the weakest area. It also effectively samples much more material because it is not restricted to one location as in most other tests. Other benefits to a fatigue test method are use of a more realistic crack, the presence of fatigue damage, the possibility of finding critical crack length, and the ability to give information on NDT temperature (this was evident

from observing arrests of the crack after each cycle in the experimental work mentioned above [22]). It is felt by some people that this type of testing should be pursued further [22].

A more conventional proposal. On the other hand, a recent study [27] has suggested a fracture control plan* for ships that calls for toughness specifications similar to existing CG, ABS, and other rules. This similarity is in specifying required toughness levels and in requiring these same toughness levels in the HAZ and weld as for base plate. Differences, however, lie in, first, calling for a minimum NDT temperature and, second, requiring toughness to be measured by the dynamic tear test (DTT) instead of the Charpy V-notch test. Due to the universality of the latter, however, correlations of Charpy energies to the DT energies were made by fracture mechanics relations [27].

It is important to note in the previous paragraph that Charpy energy criteria were also sought in the fracture control plan mentioned. The widespread use of Charpy test machines makes it very desirable to use this

---

*This study [27] advocates a two-pronged approach to fracture control: (1) specification of minimum toughness levels (discussed here); (2) the use of very high toughness crack arresters at certain locations (not discussed here).

test whenever possible so as to avoid the massive upheaval of changing established toughness test procedures. Also, there are many attempts to correlate results of expensive tests (on the research and development level) with Charpy results so that the simple test can be of practical use to industry. But, for the previously discussed study (reference [27]), there was little good correlation of Charpy energy with NDT temperature for ABS grade ship steels, which was considered a serious deficiency [28]. There are other observations of deficiencies in Charpy testing [7, 11, 17, 21, 22, 26]. It will therefore be valuable to look more closely at it due to high usage by ship classification societies and the U. S. Coast Guard; the next subsection will address more specifically some problems of the Charpy V-notch test.

III.A.3. CHARPY V-NOTCH TEST - A CLOSER LOOK PROBLEMS

The nature of the Charpy test involves deformation by severe bending loads. This causes a high degree of triaxiality which gives a severe state of strain at the notch tip. Combining these factors with the fairly high strain rate encountered, it would seem that test loading is really more severe than in-service structural loading involving fracture initiation and thus not an appropriate

way to measure notch toughness for this case. But this brings up the key point: what in-service situation is the test measuring?

NRL researchers have deemed that the Charpy test is not severe enough. They feel that it cannot accurately measure low stress crack propagation in a structure because ". . .the test is inadequate with respect to width, depth, and notch acuity, i.e., its mechanical constraint capacity is of low order." [21] Testimony to this belief is the NRL DTT which is much more severe than the Charpy V-notch test [21].

The other problem with the Charpy test is its sometimes erroneous determination of transition temperature. This was mentioned previously in comparison to DTT evaluation of ship steels [28]. NRL studies have also shown it to be especially inappropriate for high strength steels in this regard [29, 30].

SUCCESSES

Nevertheless, use of the Charpy V-notch has been extensive and, to an extent, successful. It definitely has its place for many steel types [7, 21]. One good example of this is its utilization for assessment of the ferritic steels (Subsection II.A.3; Appendix B.1).

Although NRL research has proven that the DTT is a better measure of crack propagation characteristics, there

has been successful use of the Charpy test as a fracture <u>initiation</u> assessment criterion. Regarding this, Nibbering [22], 1974, noted good correlation with Niblink tests (Appendix A.7), which measure <u>initiation</u> tendencies, and has mentioned other successful use of the Charpy test in many common low strength structural steels [22]. For instance, the 25 ft-lb energy criterion was determined to be an on-the-safe-side fracture initiation standard for most industrial applications; also, transition temperatures corresponding to this value have been considered valid [22].

Another good example of successful use of Charpy tests in low strength steels is the excellent correlation it showed with wide plate tests and Niblink tests in a very comprehensive study [31] of embrittlement in electroslag welded C-Mn steel. The author concluded that Charpy tests were indeed useful [31].

A further vote of confidence for the Charpy test was a recommendation that it, among others, be used to measure dynamic toughness, in order to prevent propagation of cracks from defects in the subcritical HAZ (to be discussed in Subsection III.B.1). This particular recommendation applied to low strength steels. In fact, it is generally felt that the Charpy test has more validity for these steels than other higher strength steels.

Regarding weldments, the Charpy test has particular value due to its small size. Specific small areas of interest, such as the HAZ, can be evaluated and compared to the surrounding area. This is the case for most weld procedure qualification toughness testing (Subsection II.A.4).

UNCERTAINTY

Use of the Charpy V-notch test in weldments is based almost entirely on experience; the fact that it has existed for so long is probably the main reason for this. The 25 ft-lb criterion, among many others, is an example. Even though these criteria have been valuable for some steels and are convenient, there is no good theoretical basis for them. Although it would be economically convenient to retain present Charpy criteria, there is increasing evidence [28, 29, 30] that use of the test should be carefully considered.

III.B. HEAT AFFECTED ZONE

II.B.1. TYPES OF BRITTLE HEAT AFFECTED ZONES

There are three more or less distinct types of HAZ. In only mild steel (C - Mn) have all three of these been observed. For this reason, and also because the experimental work of Chapter IV involves a C - Mn steel, discussion here will lean toward low strength steel. For heat treated low alloy structural steels (normalized, quenched and tempered), the types of HAZ are similar to two of the three mentioned here. The three types of HAZ are:

1) Transformed heat affected zone (THAZ)
2) Subcritical heat affected zone (SHAZ)
3) Fusion face or coarse-grain heat affected zone (CGHAZ)

TRANSFORMED HAZ

The THAZ is what is most commonly referred to when the HAZ in general is discussed. It represents the area that has been subjected to temperatures just above the A_{C1} temperature (higher temperatures cause a CGHAZ , to be discussed later). It is generally a fine-grained area at or very near the fusion line. Watkins [33], 1970, has attributed the low toughness of this area to martensite (which is generally considered to cause brittleness [33]). For C - Mn

steels, low toughness in the THAZ comes about in low heat input welds. The best way to reduce brittleness for this case is to use stress relief [33].

The above description of the THAZ is by no means rigid. Banks [32], 1974, reported that for a ferrite-pearlite C - Mn steel (ASTM A-36) the THAZ was basically the same microstructure as base plate, although less tough. In contrast, a higher strength, tougher steel (ASTM A-441) showed a bainitic (which is known to have lower toughness than ferrite-pearlite microstructures [32, 33]) THAZ and a greater percentage loss in toughness.

SUBCRITICAL HAZ

The SHAZ is peculiar to mild steels and few low alloy steels (one example is A537A mod., used by Quincy Shipbuilding Division of General Dynamics, Quincy, Mass., and some other U. S. shipyards in LNG tanker construction). This area is defined by lower temperatures (750°F to 930°F) [1, 34]; it lies up to 10 mm away from the fusion line of a weld. Chemical composition (free nitrogen) is an important cause of the embrittlement along with some form of thermal straining. Brittleness of the SHAZ can be removed by stress relief [33].

Recent studies have shown that SHAZ embrittlement can be especially bad in the presence of a pre-existing defect

or crack. The severe loss of toughness (example given below) takes place at the tip of such a defect. Dolby et al. [35], 1972, has studied this phenomenon in great detail; he has found much evidence to show that the cause of brittleness at a crack tip in the SHAZ is due to dynamic strain-ageing. Dynamic strain-ageing causes increased dislocation density and hardness at the notch tip, thus bringing about the severely lowered toughness. The recommended means of avoiding such embrittlement is to use steel with low interstitial nitrogen and a small ferrite grain size [35].

In this particular study [35], the most critical temperature for lowest toughness at the notch tip was different for two C - Mn steels: for a semi-killed steel, critical temperature was 1022°F ; for an aluminum-treated steel, critical temperature was 1202°F . The degree of embrittlement for the two steels is shown by the change in transition temperatures as follows: semi-killed steel - 72°F to 108°F increase; Al-treated steel - 43°F increase [35].

FUSION FACE OR COARSE-GRAINED HAZ

This form of HAZ is roughly defined as one where increased grain size occurs. It is always associated with high heat-input welding (electro-slag, electro-gas, and high heat submerged-arc), in all types of steels [33].

In many normalized and quenched and tempered steels, a

coarse-grained bainitic structure has appeared. Preventive measures are generally to lower the heat input. For C - Mn steels, normalizing has also been helpful [33].

DISCUSSION

Effects of HEAT in the THAZ or CGHAZ

There have been many reports, cited in reference [33], of detrimental effects of higher heat-input on notch toughness of the HAZ. So it has become common to say that higher heat input is generally undesirable.

But contradictory evidence exists. Watkins [33], 1970, cites a case where there was better toughness in a high-heat weld despite the coarser grains (the reason was attributed to autotempering of martensite). Other work [31], on 2 in. thick electroslag welds (with the added detriment of stick-electrode cross welds)*, showed that there was absolutely no loss of toughness in the CGHAZ.

Other effects

There are clearly problems with making an absolute conclusion on the effects of heat-input. This is due to many complex factors that depend on the type of welding process and type of steel. Watkins [33], 1970, has cited many of these from the literature. A few of these compli-

*This work produced a very complete correlation, involving wide plate tests, Charpy tests, and Niblink (Appendix A.7) tests.

cations are as follows:

C - Mn steels: higher heat increases the chance of burning and hot tearing; low sulfur can cause burning and greater susceptibility to hydrogen-induced cracking; in the presence of larger grains caused by higher heat input, sulfur liquidation can cause severe embrittlement [33].

Alloy steels: besides increased grain size, the presence of upper bainite can cause further embrittlement [33].

Defects

The existence of defects must also be considered along with types of HAZ's and other effects noted above. For this discussion, types of defects will be categorized as either 'typical' HAZ defects (Appendix C.1) or 'non-typical' HAZ defects. The former are those which are normally formed by the process of welding, i.e. hot cracking or cold cracking (Appendix C.1). These 'typical' defects lie close to the fusion line and are always located in the THAZ or the CGHAZ. The 'non-typical' HAZ defects, on the other hand, are associated with the SHAZ. That is, these thermally strained defects can come about first by an interruption of the welding process, whereby any defects that

formed when welding is prematurely stopped are subjected to thermal effects when the process is resumed again. The other case of thermally-strained defects in the SHAZ occurs when existing 'typical' cracks in a weld are subjected to the thermal effects of a subsequent cross weld (or any other adjacent weld). In both cases, 'non-typical' defects are subjected to the detrimental effects of thermal straining on notch toughness at the tip of the defect (Subsection III.B.1 under "Subcritical HAZ").

Initiation or propagation?

The general philosophy regarding fracture in the THAZ has been to prevent initiation from occurring at existing defects [22, 32, 33] ('typical'), as mentioned in Subsection III.A.2 under "International Institute of Welding" and "Discussion". A major reason stated for this was that a crack which initiated would most likely propagate into the base metal where HAZ toughness would no longer matter. But certain factors can cause a crack to propagate through the HAZ; these are lower toughness due to a CGHAZ, the wider brittle area caused by a CGHAZ, and those factors mentioned in III.A.2 under "Discussion, Propagation" (i.e. higher material yield strength, higher working stress, and stress relief) [22]. For such propagation through the HAZ, propagation resistance would be needed.

On the other hand, the tips of defects ('non-typical')

that are in the SHAZ have undergone such excessive embrittlement, that fracture initiation may be unavoidable. Because these brittle areas are located only at a crack tip, a propagating crack will immediately run out into surrounding tougher base material. It is thus of more importance for the surrounding material to have good propagation resistance.

III.B.2. PHYSICAL FACTORS IN EVALUATING HAZ TOUGHNESS

The absence of physical and geometric uniformity in the HAZ is obvious. The most detailed studies of these factors regarding fracture have been carried out by R. E. Dolby [35, 36, 37] and associates, of the Welding Institute in Cambridge, England.

Dolby's philosophy has been to accurately determine quantitative fracture toughness values (either K_{Ic} or critical COD) of areas of the HAZ so that corresponding critical defect sizes can be calculated. These critical defect sizes would be used to more intelligently judge if defects in the HAZ of a service weldment were severe enough to undertake repairs or not [36].

The complications of determining these quantitative fracture toughness values have been where Dolby has directed most of his efforts. These have resulted in designing different types of fracture mechanics specimens to replace

traditional specimens which suffer drawbacks in two important aspects:

1) their crack orientation with respect to the weld fusion boundary, and
2) nearness of the free surface.

Dolby recommends considering these two facets from the beginning and not being overly concerned with a conventional specimen. He refers to this as the "fitness-for-purpose" approach [36].

By taking this method of attack, a number of different test specimen designs have been developed. These are based first of all on the actual type of HAZ crack that would be encountered in service: toe cracks, root cracks, or buried (underbead) cracks (Appendix C.1). Second, these tests address cracking either longitudinal or transverse to the weld. A total of nine different specimens were originally developed, as detailed in reference [36]. Further modifications have since evolved [37].

NEARNESS OF FREE SURFACE

Looking more closely at the second drawback of conventional fracture toughness specimens, mentioned above, it is to be noted that plane strain effects are not as great near the surface. It would thus seem that a fully plane

strain fracture toughness specimen would be inappropriate for assessment of this case. But this is taken into account in applicable test specimens described in reference [36].

CRACK ORIENTATION

The other drawback mentioned above, defect orientation, entails many more considerations and uncertainties. For instance, for the same crack tip location, the crack could be directed toward the weld metal, or it could be directed 180 degrees opposite toward the base metal. Or the crack tip could be adjacent to the fusion line so that formation of a plastic zone could possibly envelope more than just HAZ material at the tip, i.e. weld metal may also be part of the plastic zone. These factors influence fracture toughness measurements, and are consequently being more carefully studied regarding the test methods discussed in references [36, 37].

Studies [37] have shown that the direction of the HAZ crack is important because it determines which specific material is included in the plastic zone. And this material could easily not be in the HAZ at all, but in the weld or base metal. Because the plastic zone determines fracture behavior, it is thus possible to have an HAZ-cracked specimen (or weldment) whose behavior has nothing to do with

HAZ properties, but with weld or base metal properties instead. This situation would be especially typical of transverse (i.e. perpendicular to weld fusion line) HAZ cracks [37].

For a longitudinal HAZ crack (i.e. parallel to the fusion line) adjacent to a weld, studies [37] have shown that the plastic zone could encompass some weld metal and initiate a fracture there instead of the HAZ. For this to have happened, however, the fracture toughness and/or yield strength of the weld metal must have been somewhat below that of the HAZ [37].

OBSERVATIONS

The detailed HAZ studies by Dolby and associates [35, 36, 37] vividly illustrate the complexities of toughness evaluation in such an intricate region. They seem to beg for a simpler yet meaningful approach to determining HAZ performance. It is believed here that this is best accomplished by using full scale weldment tests. But these tests are very expensive, and few, except the explosion bulge test, are even close to practical for use by industry and classification societies.

The Charpy V-notch test is both practical and cheap; but its validity is sometimes questionable, especially regarding weldments. Nevertheless, it is very commonly used.

The question arises as to how results from a small specimen, extracted from a weldment, correlate to the actual weldment. It may be such that no correlation exists. But, regardless, there is definitely a need to investigate fracture of the weld itself, in an inexpensive and yet practical test. This will be carried out in the experimental work to follow.

CHAPTER IV

EXPERIMENTAL WORK ON WELDED PLATE

IV.A. GENERAL

The engineering objective of this experimental work is to seek to answer the basic question of whether a weldment is safe from brittle fracture, particularly through the heat affected zone (HAZ). The definition of "safe" is considered to be the occurrence of total plasticity prior to fracture.

All weld procedure qualification tests, regardless of their specific approaches, share this same objective of determining if a structure, as a whole, is safe from brittle fracture. But they do not actually test the structure under service conditions; this is very understandable. Nevertheless, real life conditions are not achieved for these tests, generally. And it is specifically for the purpose of ensuring safety of the real life weldment that the tests exist.

The basis for doing laboratory work here is the belief that the Charpy V-notch test, which is the primary test method used for weldments, suffers from being conservative and possibly misrepresentative of the actual safety of the weldment from brittle fracture in the HAZ. A test procedure using a "weldment" (Fig. IV-1; Appendix D.1)

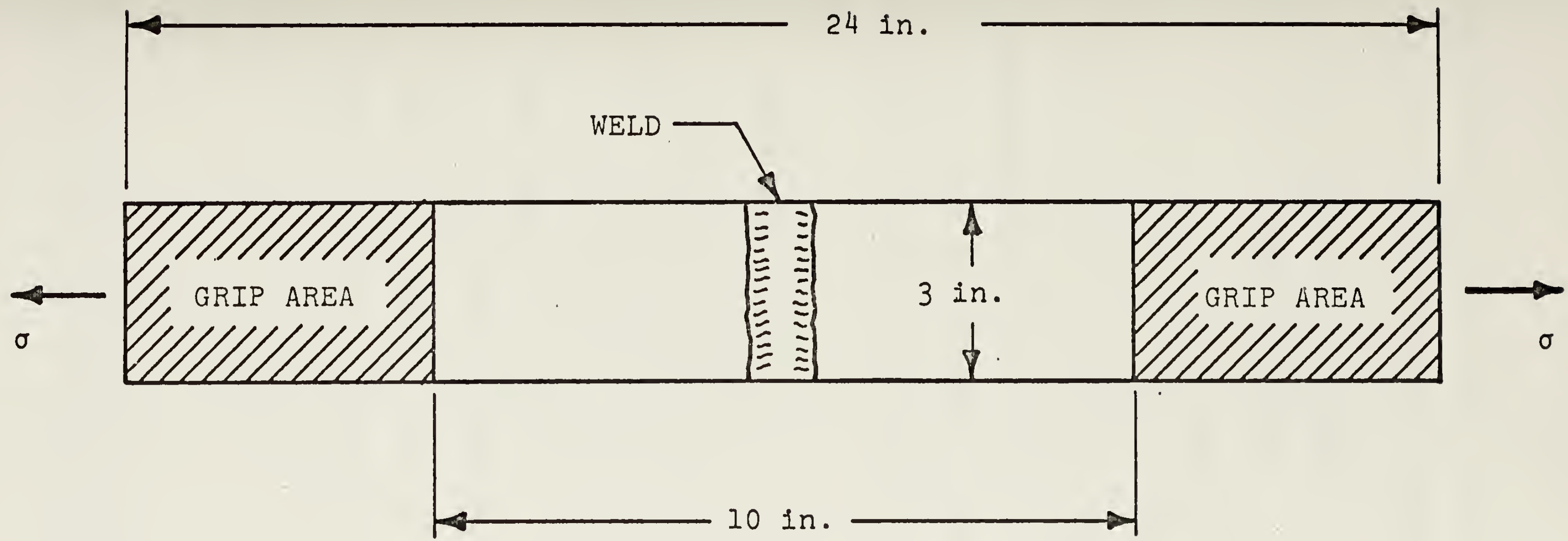

Figure IV-1. Configuration of test strip.

rather than a small specimen (like the Charpy specimen) cut from the weldment will be proposed and evaluated.

IV.B. DEVELOPMENT OF THE TEST

IV.B.1. BASIC CONSIDERATIONS

A test that will ensure the safety of the structure as a whole against brittle fracture must be realistic. That is, will a grade of "safe" in the test indicate a corresponding grade of "safe" in the structure? The choice of an actual weldment rather than a small specimen was the first step in this direction. Other considerations follow.

LOADING

The type of loading to be considered was based on two things. First it was desired to investigate the possibilities of a catastrophic fracture through the HAZ (the Type 2* fracture of Masubuchi et al. [1], 1966). Secondly, it is known that primary stresses in ship plate are tensile [38]. Therefore uniaxial tensile stress perpendicular to the length of the weld was used on the test strips. Sharp notches (fatigue cracks) were put in the HAZ to initiate fracture there.

---

*Type 2 fracture definition: propagation of a crack through the brittle HAZ without deviating away into the more ductile base metal where it could be arrested.

NOTCH CONFIGURATION

Actual weld defects are relatively small compared to plate thickness (Appendix C.1). There is also substantial plate material on either side of these defects. It was thus decided that the starter cracks in the test strips should be neither through-thickness nor through-width.

NOTCH SHAPE AND SIZE

A straight-fronted surface crack was cut into the test pieces (Fig. IV-2; Appendix D.1). The choice of this shape was due to more nearly plane strain conditions at the deepest point compared to a purely arc-shaped notch. Sharp fatigue cracks were then grown from these notches (Appendix D.2) to depths of between 50% and 70% of specimen thickness. Having the crack tip closer to the center of thickness than the surface allowed for more triaxiality [36] (for pre-plastic behavior, that is). It is evident that the size of these cracks is much greater than a typical weld defect.

NOTCH LOCATIONS

These were chosen in an attempt to locate the area of lowest notch toughness. The four locations of Fig. IV-3 were arbitrarily selected. However, fatigue cracks could only be grown successfully from locations (1) and (2) (see Appendix D.2); thus no test results could be obtained with notches in locations (3) or (4) (Charpy

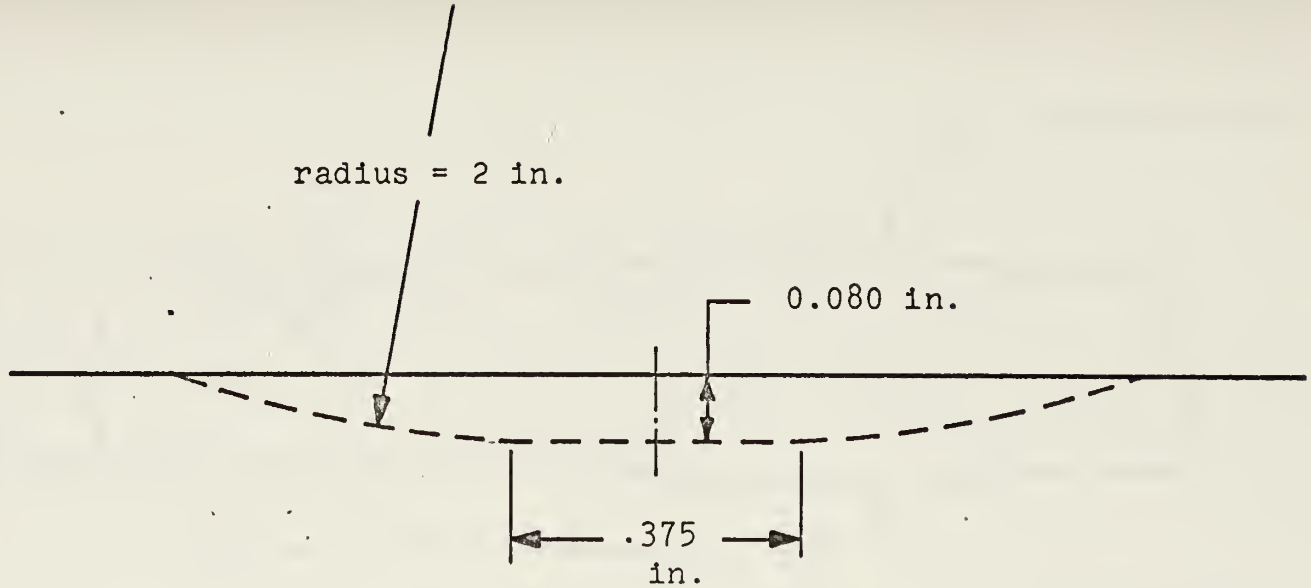

Figure IV-2. Notch configuration.

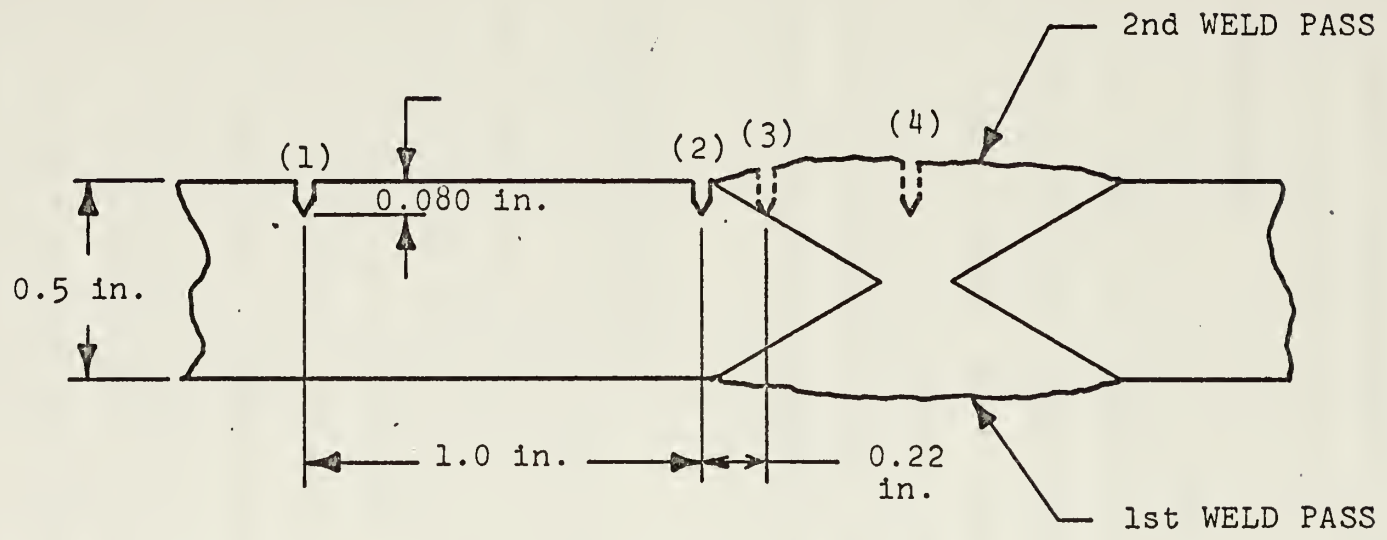

Figure IV-3. Notch locations. Test strip notches were placed at (1) and (2) only. Charpy specimen notches were placed at all four locations.

V-notch specimens were obtained for all four areas, however). The side of the second weld pass was notched due to slightly greater brittleness (as indicated by higher hardness values, Subsection IV.C.3).

LOADING RATE

One factor that was less realistic in the test was the slower (by a factor of 1/400 to 1/163) loading rate than a ship would encounter (Subsection IV.D.2; Appendix C.4). But it was felt that more control in conducting the test was attainable by using slower loading. Also, the velocity-modified temperature [39] relation (Appendix C.3) will be used to predict the effects of changes in loading rate.

IV.B.2. EVALUATION CRITERIA

It was stated earlier that the engineering objective of this experimental work is to determine if a weldment in a ship is safe from brittle fracture through the HAZ. The definition of safe was very succinct (occurrence of total plasticity prior to fracture) as mentioned in Section IV.A. But more information than a simple answer of yes or no to the safety question can be gotten in running a test strip. It is the purpose of this subsection to explain which information will be sought and how it is to be used to interpret and evaluate test results.

HOW SAFE?

The first question that arises after determining if a weldment is safe is the question of how safe (plastic behavior). It was initially proposed to approach this by using the ultimate tensile extension in fracturing an unwelded strip of steel as the standard to compare with the amount of extension that occurred in fracturing a notched, welded test strip. But, the narrowness of these test strips compared to an actual ship structural plate was felt to be a cause for erroneous information. That is, the measurement of extension over a gage length would not correlate accurately to the real thing because of the numerous variables involved. So, it was decided to use the reduction in specimen thickness, or thinning, on the fracture surface instead as a measure of ductility. Also, the crack opening angle [40] (Appendix C.3) will be used. These parameters will be evaluated regarding (1) their dependence on temperature, and (2) their values in relative assessment (explained below) of the two types of specimens (base metal notch and HAZ notch).

HOW UNSAFE?

Alternatively, the question of how unsafe (brittle behavior) the piece is might also be of concern. Measurement of this factor could be done with a K_{Ic} or J_{Ic} value (see Appendix C.2). However, the question of how

safe or how unsafe might simply be an academic one if the temperature transition from ductile to brittle occurred near a feasible service temperature. It was for this reason that the idea of obtaining a K_{Ic} or J_{Ic} for brittle fracture was scrapped. The occurrence of a few brittle fractures in test strips indicated the dominance of fracture appearance transition temperature.

RELATIVE ASSESSMENT

There is no entirely reliable method of applying parameters measured on a test piece to a structural weldment and expecting good correlation. So it was thought that some relative assessment of the different areas of the weld could offer the best information. This means that behavior with a notch in the unaffected base metal is compared to behavior with the notch in the area of interest (HAZ). It is common to assess welds by screening such as this. Its value, for purposes of this study, is that not only could a contrast be drawn with Charpy V-notch test screening, but also, more important, the safeness of the HAZ could be determined relative to the base metal.

SUMMARY

The major parameters to be used as evaluation criteria are as follows: fracture appearance transition temperature, fracture surface thinning, and crack opening angle (COA) [40], both in the HAZ and base metal.

IV.C. MATERIAL AND WELDING DETAILS

IV.C.1. MATERIALS

BASE METAL

ASTM A-36 steel was used as base plate (1/2"). Its chemical composition is shown in Table IV-1, and its mechanical properties are as shown in Table IV-2.

WELD METAL

Two manual submerged-arc weld passes were made with a 5/64 inch diameter L-60 electrode/860 flux combination (Lincolnweld® 860 Flux L-60 Electrode Combination, classification F62-EL12). Tests required by specifications AWS A5.17-69 and ASME SFA 5.17 showed the chemistry and mechanical properties of deposited weld metal to be as shown in Tables IV-3 and IV-4 (ref. Test Certificate for this flux-electrode combination).

An initial manual-arc root pass with a 1/8 inch 7018 low hydrogen electrode was made prior to the two main passes with the L-60 wire.

IV.C.2. WELDING

Initial surface preparation for welding is shown in Fig. IV-4. The root pass was then made in the vee. Next, a manual submerged-arc pass was made over the root pass. The side opposite the original vee was then prepared for the second submerged-arc pass by back-gouging.

TABLE IV-1

Chemical composition of A-36 base metal

Element :	C	Mn	Si	P	S
% comp. :	0.21	0.69	0.04	0.015	0.018

TABLE IV-2

Mechanical properties of A-36 base metal

Yield point	Tensile strength
40,400 psi	63,600 psi

Elongation in 8 in.	Impact properties
27%	none specified

TABLE IV-3

Chemical composition of weld metal in L-60 electrode (reference Test Certificate)

Element :	C	Mn	Si	P	S
% comp. :	0.077	0.88	0.22	0.019	0.015

TABLE IV-4

Mechanical properties of weld metal for L-60 electrode/ 860 flux combination (reference Test Certificate)

Yield point	Tensile strength
58,800 psi	70,200 psi

Elongation in 2 in.	Impact properties
29%	63 ft-lbs (-20°F) (Charpy V-notch)

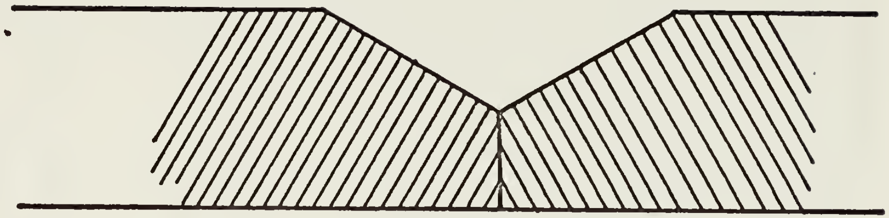

Figure IV-4. Initial surface preparation for welding.

The current for both submerged-arc passes was 360 amperes. Speed of travel was 9 inches per minute. Current for the initial root pass was 150 amperes.

The photograph (Fig. IV-5) shows the detailed cross-section of the weld metal. The second pass is the upper one in each weld shown in Fig. IV-5.

IV.C.3. HARDNESS MEASUREMENTS

Table IV-5 indicates that there was a distinct difference between hardness on the surface of the first and second weld pass, for both weld metal and HAZ. The tempering effect of the second pass reduced hardness on the opposite surface by 8 - 9% .

It can also be seen from Table IV-5 that the HAZ did undergo hardening and thus embrittlement with respect to the base metal.

By traversing the HAZ on the surface of the second weld pass, average hardness measurements were obtained as shown in Fig. IV-6.

Some hardness readings were taken on the shear-cut sides of the test strips. These were roughly 10% greater than the surface hardness readings of Table IV-5 (showing that the hardening effect of the shearing was not totally removed by the subsequent milling of the sides). Never-the less, the same trends as above were noted in these

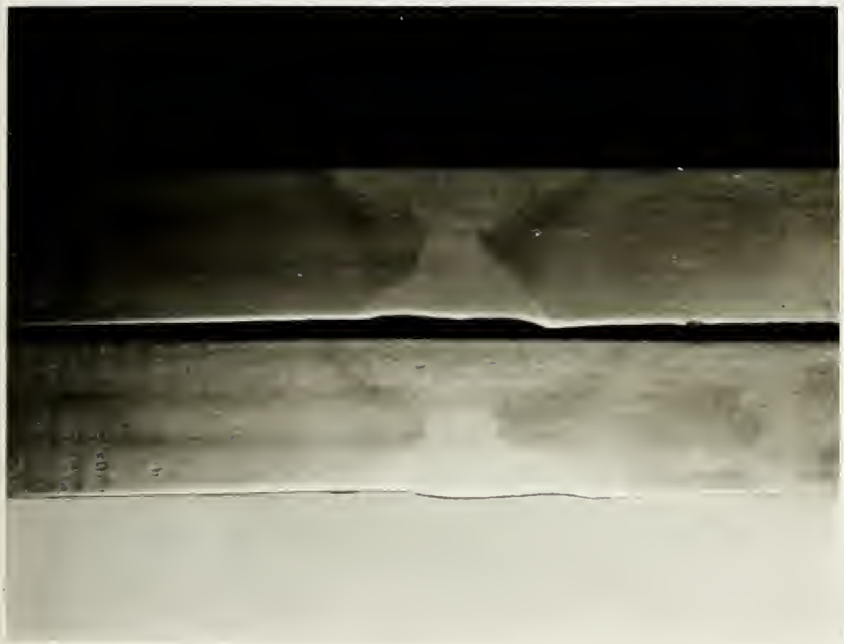

Figure IV-5. Photo of weld cross-section.

TABLE IV-5

Surface Hardness of Weldment

AREA	WELD PASS NO.	SURFACE HARDNESS (average) (Rockwell B number)
HAZ	1	75.8
	2	83.3
WELD METAL	1	82.0
	2	88.7
BASE METAL	-	75.2

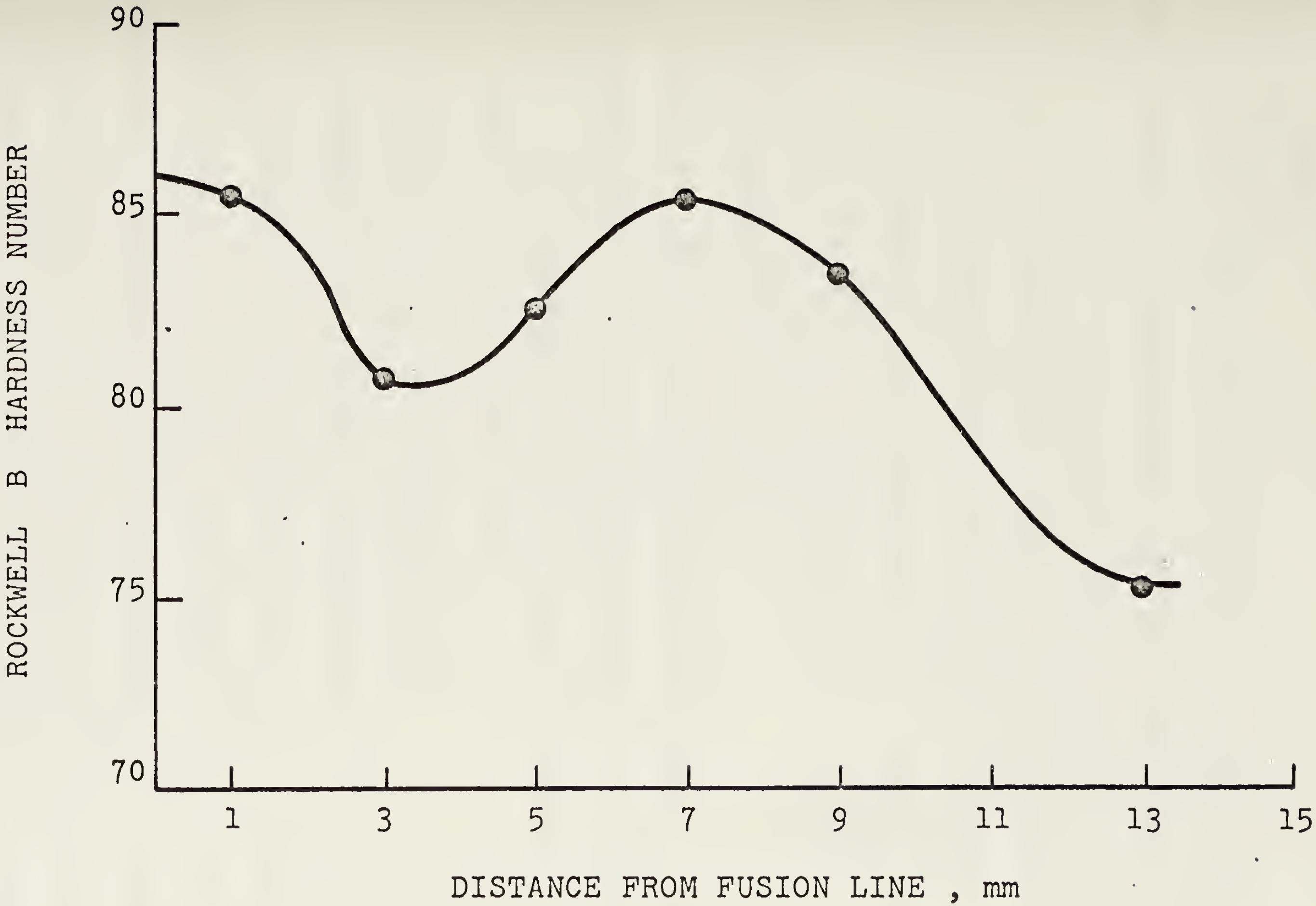

Figure IV-6. Plot of hardness versus distance from fusion line on the surface of the second weld pass.

measurements.

IV.C.4. COMMENTS

Because this was not a high heat input weld, it is expected that no coarse-grained HAZ (Subsection III.B.1) appeared. But due to the type of steel, there could easily exist a sub-critical HAZ (Subsection III.B.1) along with the conventional transformed HAZ (Subsection III.B.1). The presence of a SHAZ may be indicated by the jump in hardness at 7 mm from the surface fusion line (Fig. IV-6).

IV.D. RESULTS AND DISCUSSION

Plots of evaluation parameters are shown in Figs. IV-7 through IV-11. Data for each fracture is given in Table IV-6. Photographs of all fracture surfaces are shown in Figs. IV-17 through IV-33.

IV.D.1. SAFETY OF THE HEAT AFFECTED ZONE

PRIMARY TEST RESULT: ACCEPTABILITY OF HAZ

The Charpy energy values, obtained to provide a comparison with the new test, are shown in Fig. IV-7. The HAZ specimens (which had not even reached their transition temperature) showed a much lower transition temperature than the base metal specimens. From this it is evident that the HAZ has considerably lower Charpy V-notch toughness. However, in direct contrast, the fracture appearance

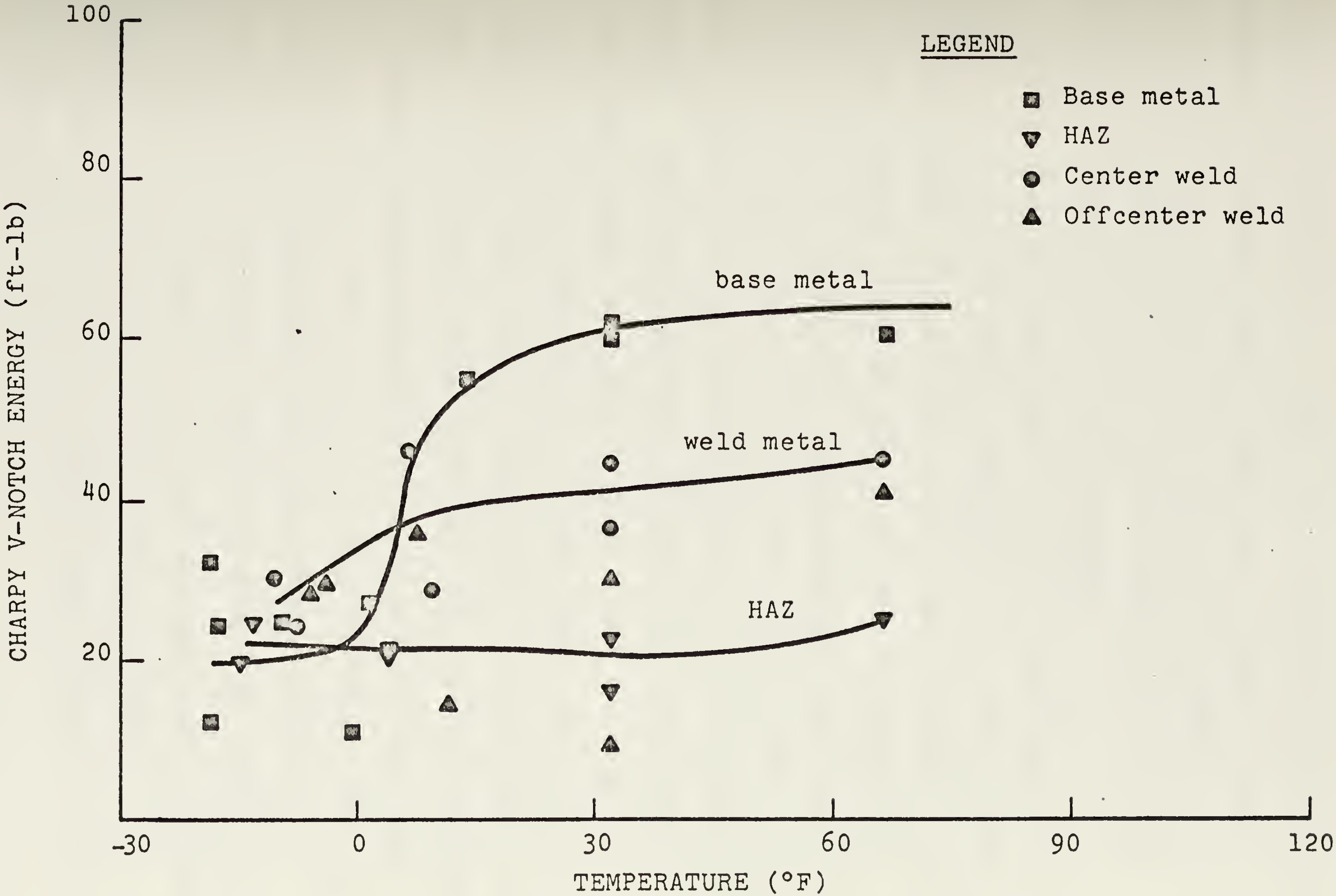

Figure IV-7. Charpy V-notch energy curves for specimens extracted from the weldment at the four locations noted in Subsection IV.B.1, Fig. IV-3.

transition temperatures (Fig. IV-8) obtained from the face-cracked test strips used in this new test are the same in the HAZ and base metal. This significant conflict of results indicates that lower notch toughness in the HAZ may be acceptable in an actual weldment.

Other ductility parameters from the test strips also bear on this point. These parameters are center thinning of the fracture surface (Fig. IV-9), edge thinning of the fracture surface (Fig. IV-10), and crack opening angle (Fig. IV-11; Appendix C.3). In comparing these parameters for HAZ and base metal fractures with fully plastic appearance, there is little solid evidence of less ductility in the HAZ. Edge thinning (Fig. IV-10) shows the greatest difference between the base metal and HAZ, but there is little difference for center thinning (Fig. IV-9) and crack opening angle (Fig. IV-11; Appendix C.3). There was, however, one definite dissimilarity between plastic fractures of the HAZ and base metal that is not evident from these ductility curves (Figs. IV-9, 10, 11). This was the large deviation of crack direction (Fig. IV-12) in HAZ test strips versus base metal (also see Table IV-6, "Angle on one fracture surface"). The cause was the harder adjacent weld metal rather than lower HAZ notch toughness. This effect may have caused the smaller edge thinning in the HAZ fractures (Fig. IV-10).

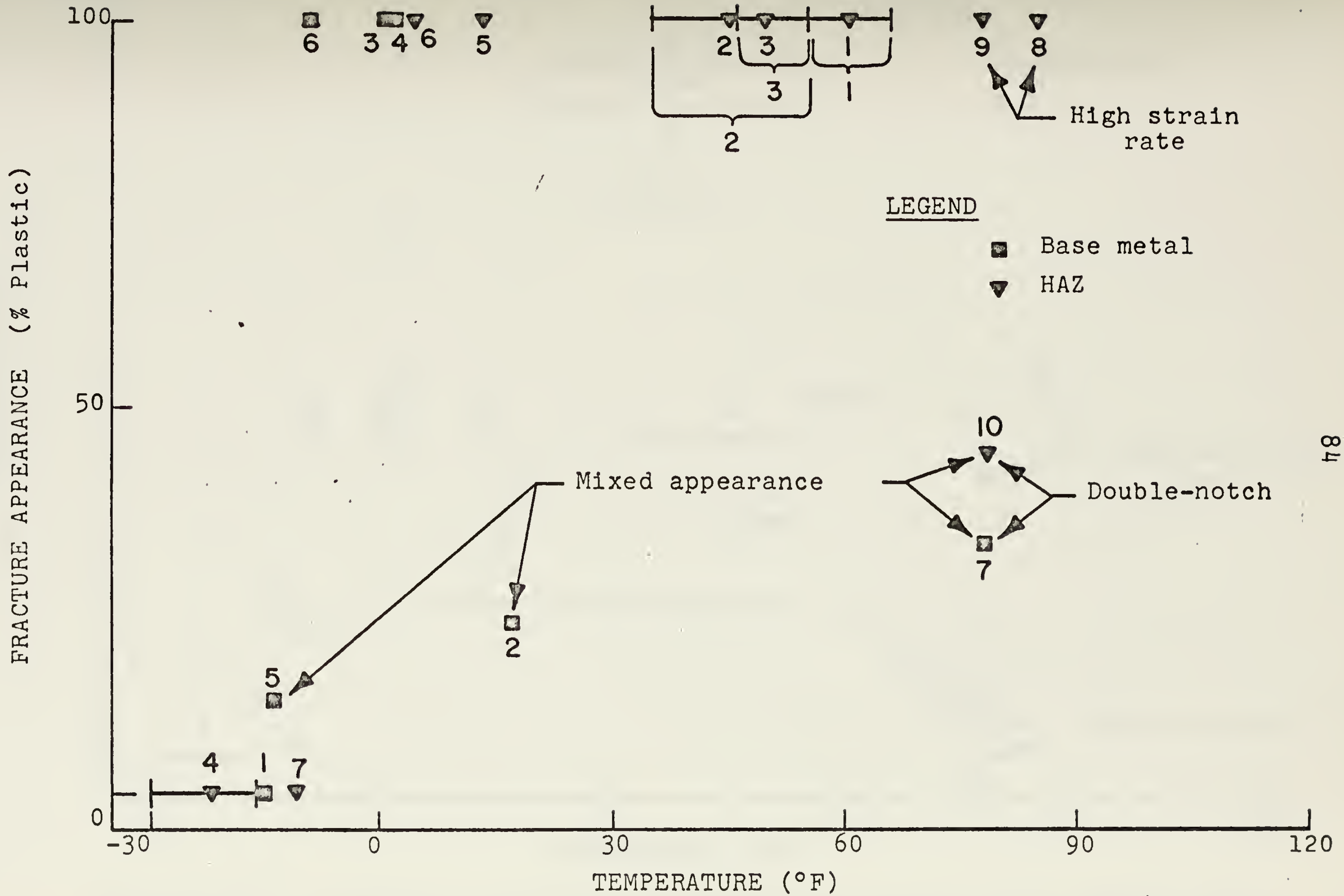

Figure IV-8. Description of the appearance of fracture vs. temperature for each strip. Specimen numbers and any major uncertainties in temperature are shown.

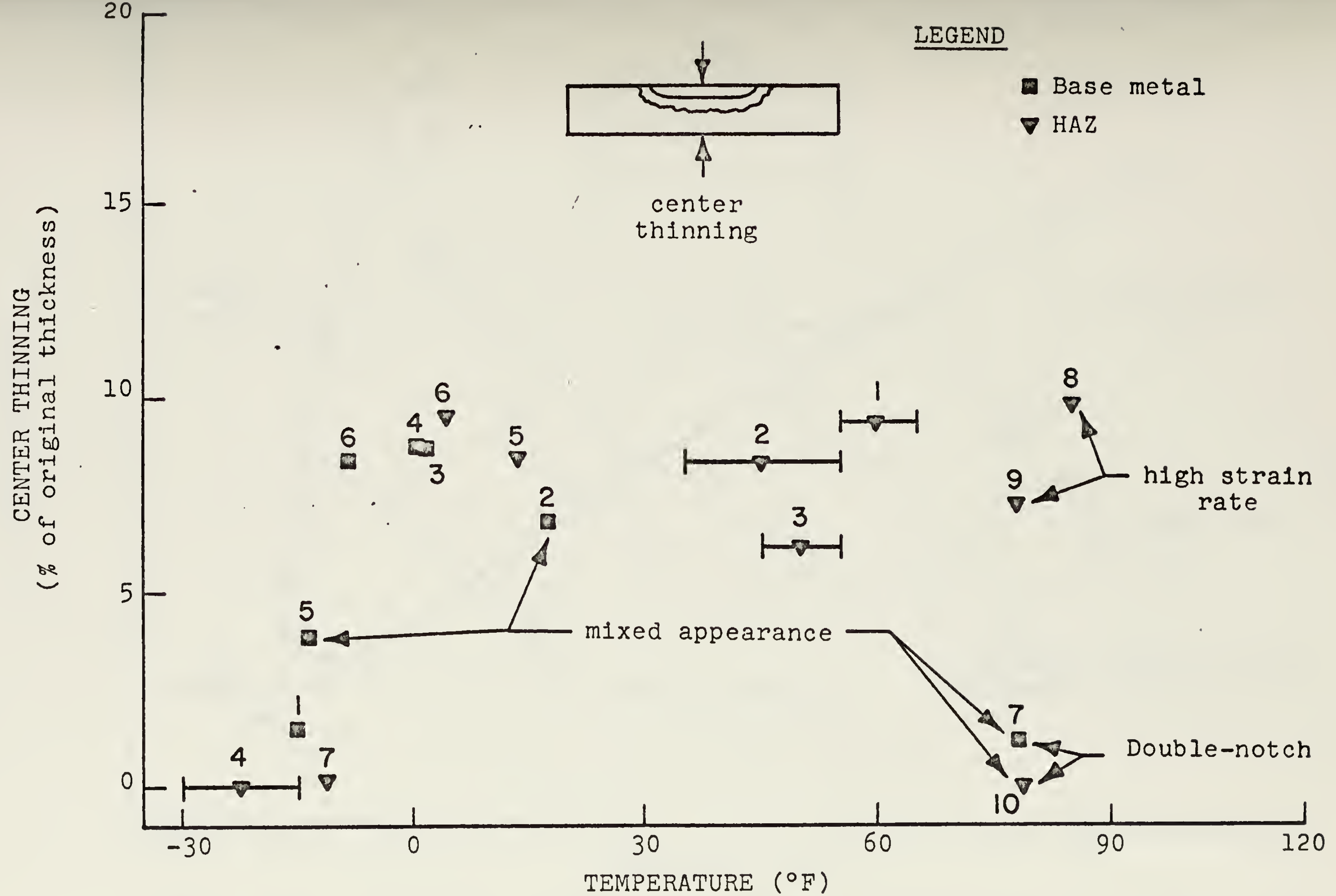

Figure IV-9. Ductility, depicted as reduced thickness at the <u>center</u> of the fracture surface, vs. temperature for each test strip. Specimen numbers and any major uncertainties in temperature are shown.

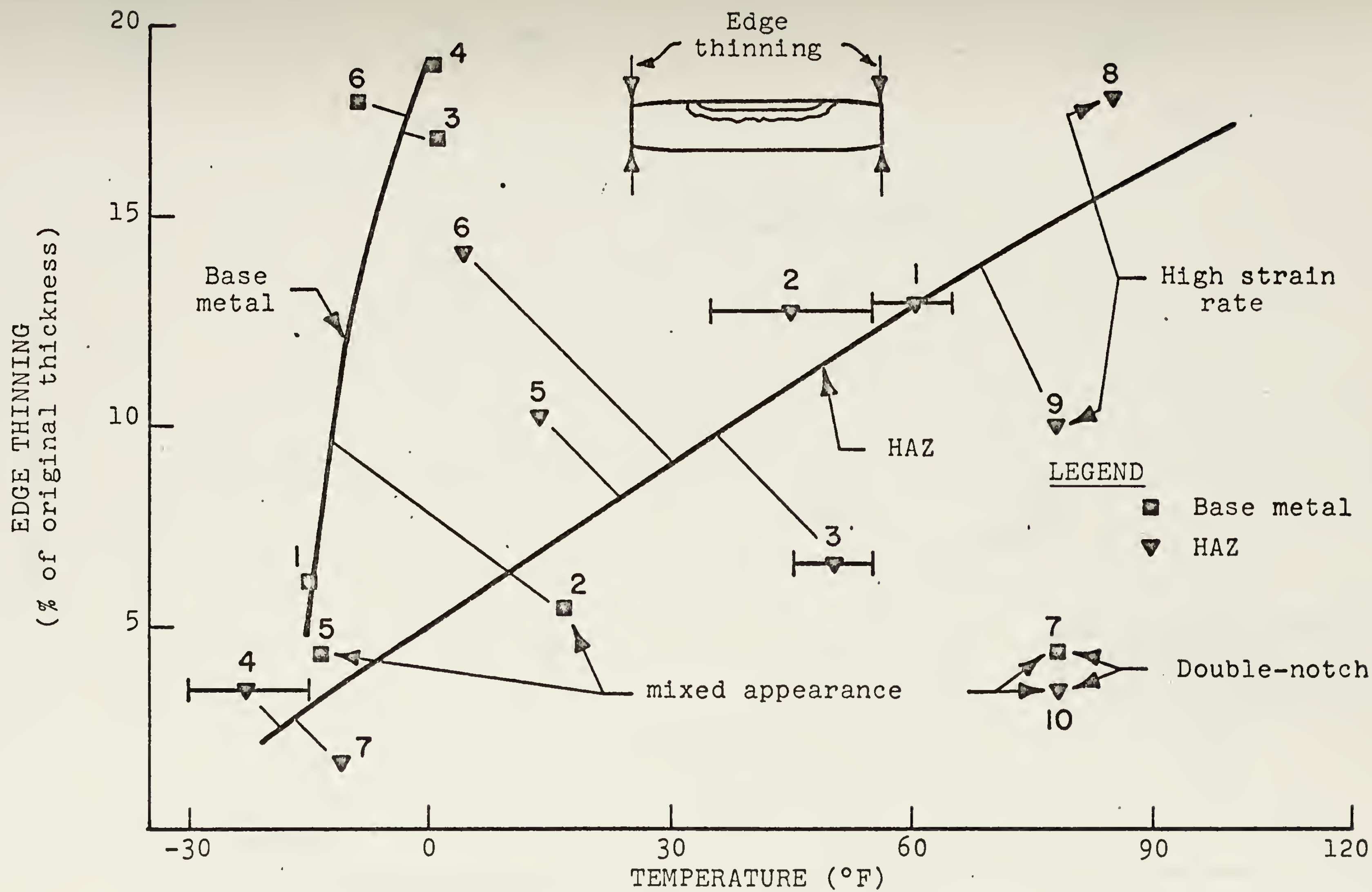

Figure IV-10. Ductility, depicted as reduced thickness at the <u>edges</u> of the fracture surface, vs. temperature for each test <u>strip</u>. Specimen numbers and any major uncertainties in temperature are shown.

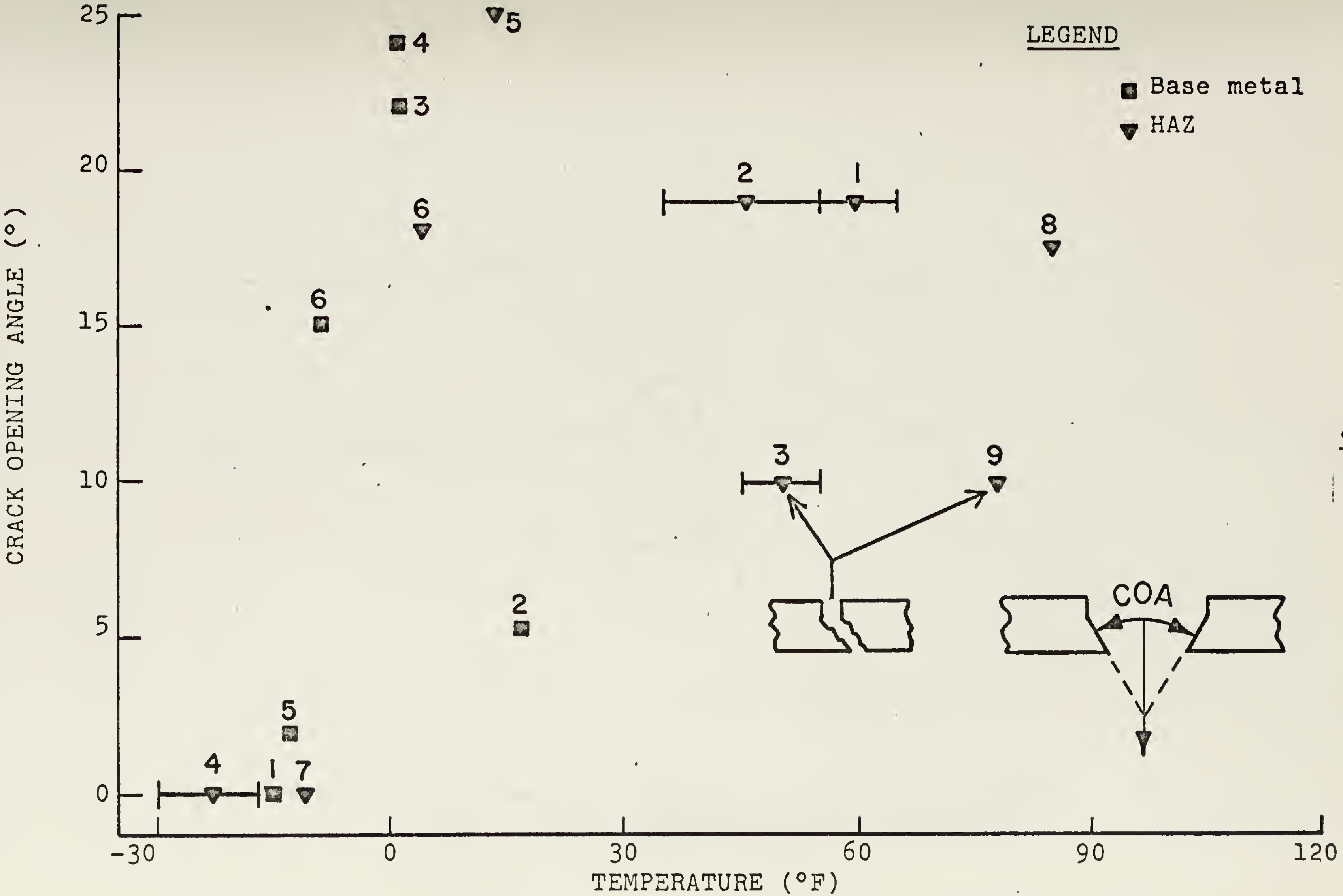

Figure IV-11. Ductility, depicted as crack opening angle (COA), vs. temperature for each test strip. Specimen numbers and any major uncertainties in temperature are shown.

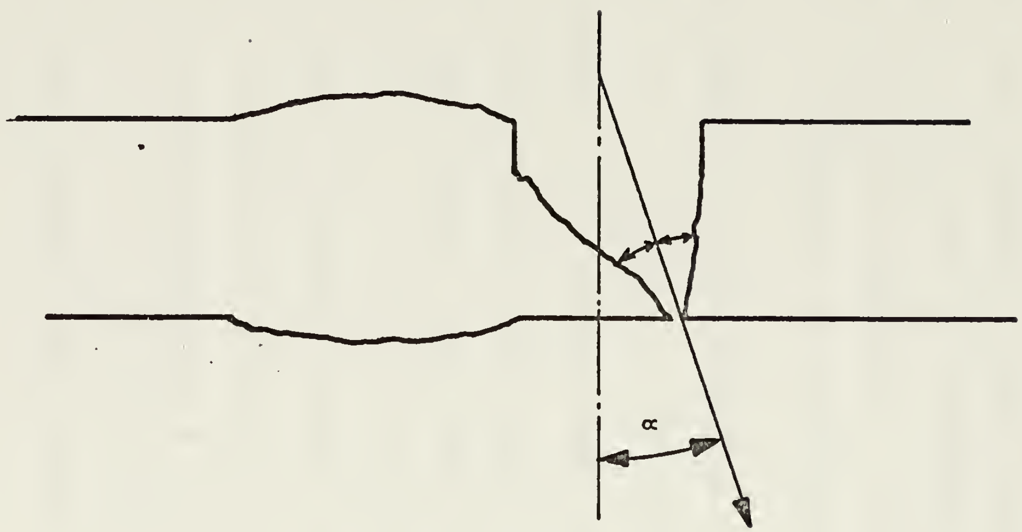

Figure IV-12. Non-symmetrical nature of plastic fractures in the HAZ, as evidenced by the deviation angle, α , of crack direction from the vertical.

In summary, low Charpy V-notch toughness in the HAZ had no effect on HAZ fracture of the welded test strips in this experimental work. Possible explanations for this result will be presented next.

DISCUSSION OF HAZ ACCEPTABILITY

There are factors associated with these strip tests that must be considered before concluding that low Charpy toughness in the HAZ is acceptable. They involve (1) crack depth and weld geometry, (2) notch orientation, and (3) relative properties of the weld zone.

Crack depth and weld geometry

Due to the deviation of the fusion line from vertical, the distance, x , of the crack tip from the fusion line (Fig. IV-13) increases with depth. This results in the crack tip being further away from the most brittle HAZ material, which is most likely the transformed HAZ (THAZ) (Subsection III.B.1), adjacent to the fusion line.*

It should be noted that some portions of the curved ends of the crack tip perimeter did lie in areas closer to the fusion line (of the second weld pass), these areas being nearer to the surface (Fig. IV-2). But results for

*This is uncertain; the most critical area could be the sub-critical HAZ (SHAZ) instead (Subsection III.B.1, IV.C.4).

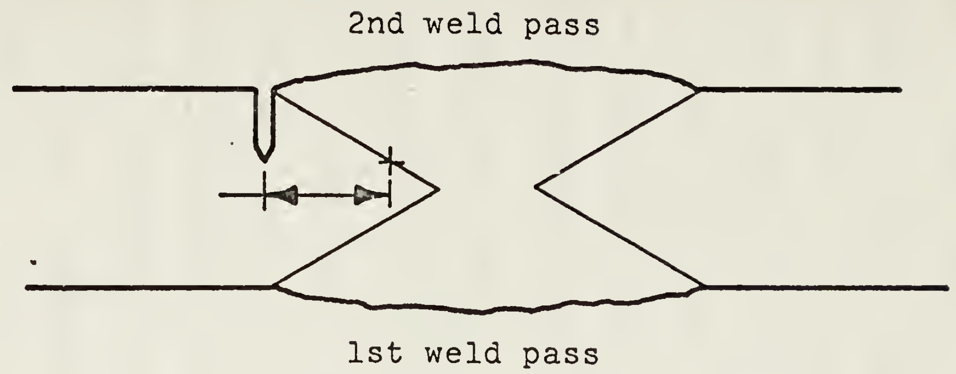

Figure IV-13. Distance, x , of the crack tip from the fusion line of the second weld pass.

HAZ specimens were such that fracture was dominated by the deepest portion of the crack; the lower degree of triaxiality nearer the surface apparently negated the effect of more brittle material there.

In some cases the crack tip extended below the mid-thickness of the plate and thus approached the fusion line of the <u>first</u> weld pass. This could have either of two possible effects: (1) by getting closer to a fusion line the crack tip approached more brittle material, or (2) the material in the HAZ of the first weld pass was less brittle due to the tempering effect caused by the second weld pass (noted by the hardness measurements, Table IV-5).

<u>Notch orientation</u>

The Charpy specimens had a TL orientation [41] (notch plane normal to the larger TRANSVERSE direction of original plate, propagation in the LONGITUDINAL direction of the plate) as shown in Fig. IV-14. The effect of this was to sample nearly all the material through the thickness of the plate. An averaging effect, so to speak, results from this. In contrast, for the cracked test strips, the deepest portion of the crack sampled only a very specific depth in the thickness, which may not be the most brittle portion of the HAZ as noted in the previous discussion ("Crack depth and weld geometry"). The

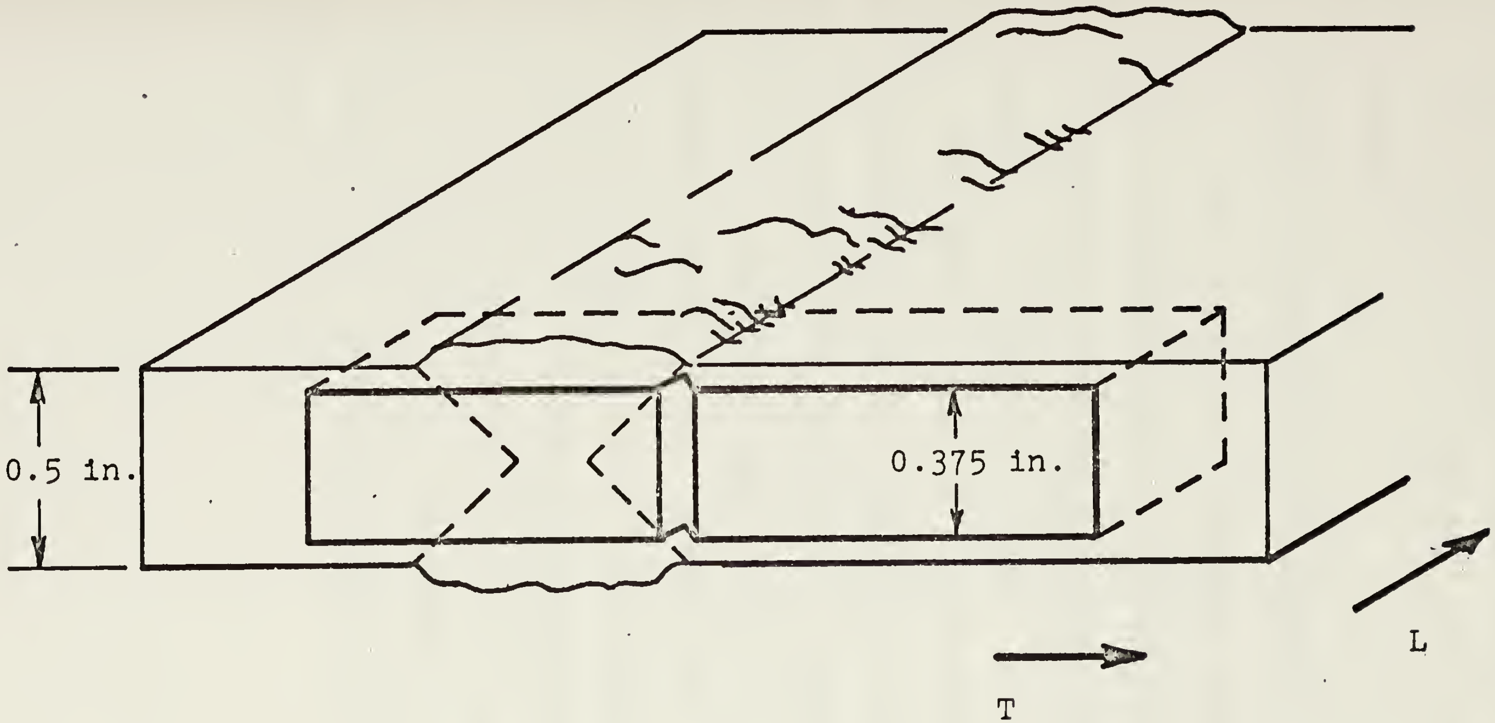

Figure IV-14. Orientation of Charpy V-notch specimen extracted from the HAZ of the weld.

fact that the Charpy specimen does include the more brittle material could thus account for its more pessimistic results in the HAZ.

Relative properties of weld zone

Some other factors to consider in why the low Charpy V-notch toughness made no difference are the relative yield strengths of the HAZ and base metal, and the width of the HAZ. As Masubuchi et al. [1] (1966) noted, higher yield strength of the HAZ could prevent Type 2 [1] fracture (Subsection IV.B.1, "Loading"); this may have entered in for these test results too (the HAZ did have higher ultimate tensile strength as shown by the higher hardness, Subsection IV.C.3). It was also noted in reference [1] that a narrow area of low toughness is preferable to a wider one in preventing catastrophic HAZ fracture (Type 2 [1]). For this experimental work the HAZ is relatively narrow (compared to an electroslag weld, for instance, or some other high heat input weld); this may have contributed to the results.

IV.D.2. OTHER FACTORS AFFECTING SAFETY

DOUBLE-NOTCHED TEST STRIPS

Two test plates, numbers BASE-7 and HAZ-10 (Figs. IV-23 and IV-33), were notched (but not fatigue-cracked) on both sides of the plates. The reason for doing this was to investigate the effects of the more severe plastic triaxiality caused by opposed notches [42]. The results of these two pieces are very significant: partially brittle behavior was observed 80 degrees above the transition temperature for single-notched test strips! This is a vivid illustration of the consequences that two opposed cracks could have in a weldment, even though the chances of encountering this situation may be slim. It shows that initial plasticity when fracture commences is not necessarily a guarantee that fracture will continue in a plastic manner. The reason is directly attributable to the greater stresses due to the modified plastic slip line field [42]. The safety of the weldment is thus seriously lowered by this situation.

STRAIN RATE

Loading rates for a ship in a storm are roughly 10,000 to 25,000 psi/sec (Appendix C.4). When compared to the average strain rate in the test strips, 61.5 psi/sec (Appendix C.4), ship rate is larger by a factor of

163 to 400 . Using the velocity-modified temperature [39] relation (Eq. C-3), corresponding increased transition temperatures are 42°F to 50°F . Thus it is clear that use of slower-than-real-life rates in this experimental work gives more optimistic (lower) values of transition temperature.

<u>Experimental investigation of rate effects</u>. Two specimens (HAZ-8, Fig. IV-31, and HAZ-9, Fig. IV-32) were run at higher load rates (see Table IV-6). But the maximum rate attainable with the tensile machine was not enough to get brittle fracture at room temperature (increased transition temperature is 24.6°F*). It was also noted that this increased rate had no effect on the ductility parameters (center thinning, Fig. IV-9; edge thinning, Fig. IV-10; and crack opening angle, Fig. IV-11, Appendix C.3).

<u>Running cracks</u>. An important consideration for fracture of in-service welded plate is the effect of a fast running crack (Subsection III.A.2, "NRL" and "Discussion"); this exposes the material ahead of the crack to very high rates, i.e. loading in microseconds. If this is to be

---

* For an increased rate of $19.5 : 1(\frac{1800}{92.25})$ (Table IV-6; Appendix C.4), Eq. C-3 gives 24.6°F as the increased transition temperature.

prevented, the material must be able to arrest such a propagating crack. The test method used in this experimental work cannot measure arrest capability - it measures tendency for crack initiation only. However, the double-notched test strips could conceivably measure arrest capability; the opportunity for arrest arises when the crack propagates away from the area of high triaxiality between notch tips at the center of the specimen width.

EFFECT OF TEMPERATURE ON DUCTILITY

In the plastically - fractured test strips, the amount of ductility was generally not dependent on temperature (Figs. IV-9, 10, 11). In fact, the scatter in values of center thinning (Fig. IV-9) and crack opening angle (Fig. IV-11) among plastic fractures indicates less relative importance of these parameters among fully plastic fractures. It is only the transition temperature which will alter them significantly. Thus the matter of safety depends only on this temperature. Degree of safety, as measured by center thinning (Fig. IV-9) and crack opening angle (Fig. IV-11) is unimportant.

But, in direct contrast, edge thinning in HAZ fractures showed temperature dependence (Fig. IV-10). As transition temperature is approached, the lower ductility values give indication of this, which is favorable in that

it gives warning of approaching transition temperature. It was, nevertheless, inconsistent with most results (noted in previous paragraph).

STRESS STATE

It could be argued that these uniaxially stressed test strips are not a realistic simulation of some real life structures. The best example is pressure vessels, which have biaxial applied stress. This multi-axial stress state could increase severity. But the crack itself in the test strips causes triaxiality which may also be as severe, or more so. Detailed analysis would be required to determine this for certain. At any rate, for the case of primary loading of a transverse weld in a ship's hull, which the test was aimed at simulating, uniaxial tensile stress is realistic.

However, residual stresses were probably not present in the test strips, whereas they usually are in a structural weldment. The stress state would no longer be uniaxial in this situation, and this test might thus be misrepresentative.*

*It should be kept in mind that residual stress would be reduced or eliminated by general yielding, so that its predominant effect would be for brittle fracture.

SPECIMEN WIDTH

The biggest drawback of the narrow (3 in.) test strip is that it cannot indicate a catastrophic Type 2 [1] HAZ fracture (Subsection IV.B.1, "Loading") - there simply is not enough weld length for the crack to run. It appears that the only adequate means of checking this type of fracture is by expensive wide plate tests.

Specimen narrowness could have affected plastic behavior due to the crack edges being close to the sides of the test strip. Behavior might also be prejudiced for cases where the crack was unsymmetrical, but there was no evidence of this.

IV.D.3. FURTHER TEST RESULTS

VARIATION IN CRACK DEPTH

Attaining cracks of constant depth was difficult. Thus it was suspected that variable crack depth would have some effect on test results. But a plot of edge thinning and center thinning versus crack depth (Fig. IV-15) shows that crack depth has no effect.

INABILITY TO GROW FATIGUE CRACKS IN WELD

As noted under Subsection IV.B.1, attempts were made to grow fatigue cracks from notches in the weld metal. However, in all such cases a total fatigue fracture occurred

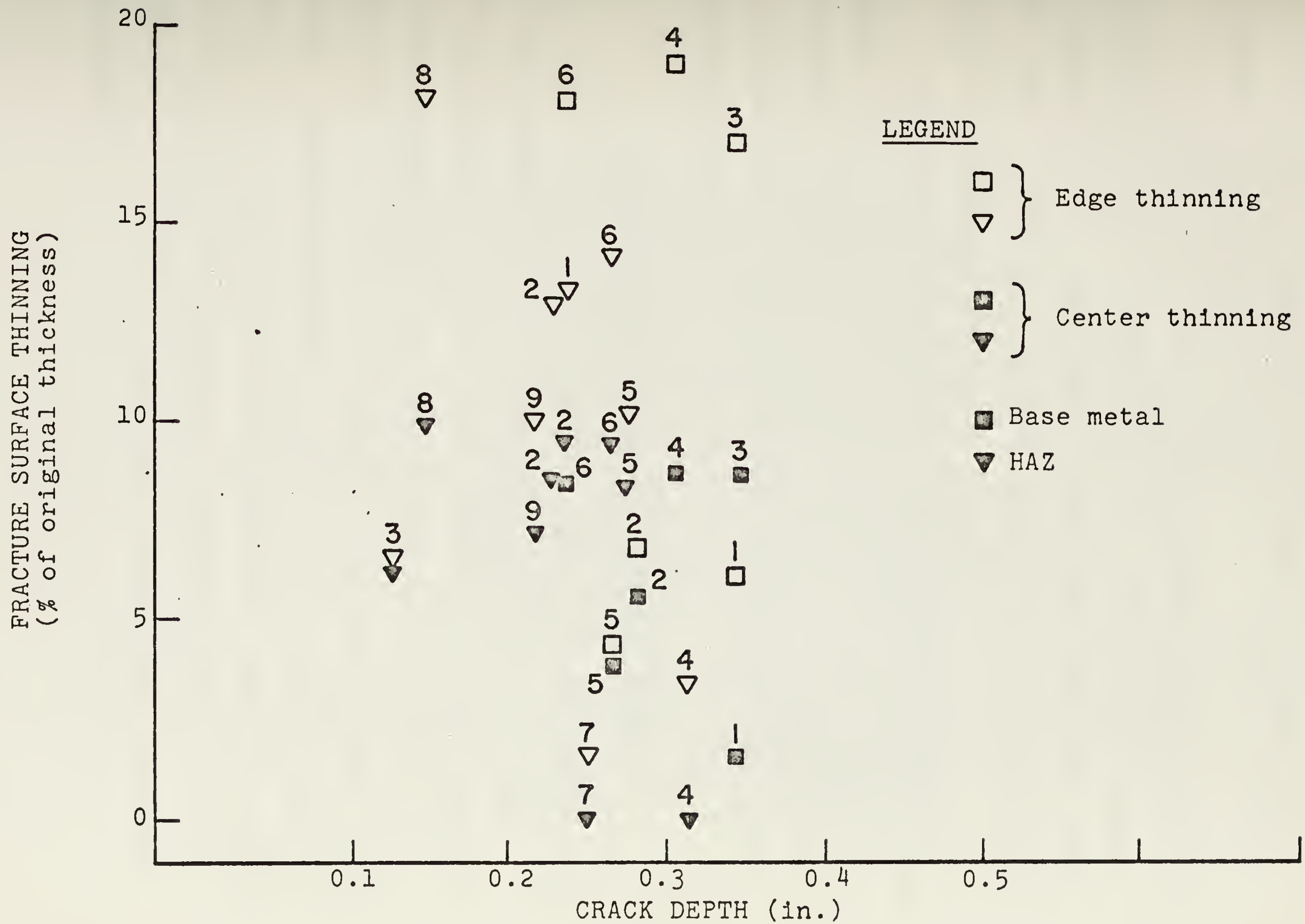

Figure IV-15. Ductility, depicted by fracture surface thinning at both center and edges, vs. crack depth for each test strip.

at the surface fusion line in the HAZ, away from the desired location (Fig. IV-16).

The reason for this is the greater thickness of the weld metal and its higher strength. These two factors combined to give weld crack growth rates that were only 40 - 50% of HAZ crack growth rates. (This is shown in detail in Appendix D.2.)

Another factor which may have encouraged lower crack growth rates in the weld is its higher Charpy V-notch toughness compared to the HAZ. Also, it was seen that some small toe cracks in the HAZ acted as the points of fatigue fracture initiation.

BRITTLE-DUCTILE BEHAVIOR IN BASE METAL

Two test plates (BASE-2, Fig. IV-18; BASE-5, Fig. IV-21) showed signs of initial plastic tearing at the deepest portion of the crack. However, cleavage fracture, which emanated from the sides of the fatigue crack, soon dominated. It was surprising that this would occur in base metal - similar behavior would be expected in the HAZ, instead, where material at the crack sides nearer the surface is more brittle (as discussed in Subsection IV.D.1 under "Discussion of HAZ Acceptability - Crack depth and weld geometry").

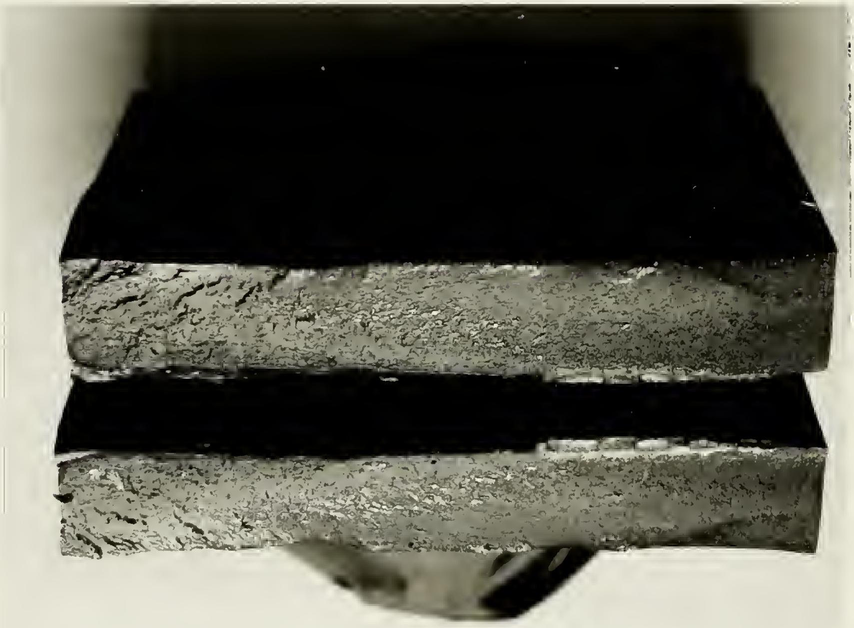

Figure IV-16. Photo of fatigue fracture of a weld metal-notched test strip.

IV.E. CONCLUSIONS

The following conclusions can be drawn from the test results presented:

1. Safety of a welded steel structure depends primarily on the ductile-to-brittle transition temperature (Subsection IV.D.1).

2. This transition temperature is affected strongly by the presence of two opposed notches (Subsection IV.D.2, "Double-Notched Test Strips").

3. Low Charpy V-notch toughness in the heat-affected zone of a weldment will not necessarily degrade the fracture performance of the weldment (Subsection IV.D.1).

TABLE IV-6

DATA SUMMARY

TEMP (°F)	TEST STRIP NUMBER	FRACTURE APPEARANCE	STRAIN RATE ($\times 10^{-4}$/sec)	LOAD RATE (lb/sec)
-15	BASE-1	Brit.	-	278
-13.5	BASE-5	Mixed	2.3	91
-9	BASE-6	Plas.	3.9	133
0.5	BASE-4	Plas.	1.1	147
1.0	BASE-3	Plas.	-	20
17	BASE-2	Mixed	-	88
78	BASE-7 (2-notch)	Mixed	6.6	143
<15	HAZ-4	Brit.	-	250
-11	HAZ-7	Brit.	3.5	78
4	HAZ-6	Plas.	2.0	67
13.5	HAZ-5	Plas.	2.4	93
35-55	HAZ-2	Plas.	-	10-15
45-55	HAZ-3	Plas.	-	10-15
55-65	HAZ-1	Plas.	-	10-15
85	HAZ-8	Plas.	30	1160
78	HAZ-9	Plas.	-	1800
78	HAZ-10 (2-notch)	Mixed	6.6	98

CENTER THINNING %	EDGE THINNING %	ANGLE ON ONE SURFACE (°F)		COA (a + b) (°F)	CRACK DEPTH (in.)
		a	b		
1.6	6.1	0	0	0	.344
3.9	4.4	2	2	4	.266
8.4	18	7	8	15	.234
8.7	19	11.5	12	24	.305
8.7	17	11	11	22	.344
6.8	5.6	3.4	2	5.4	.281
1.2	4.4	-	-	-	-
		weld	base		
0	3.5	0	0	0	.313
0	1.7	0	0	0	.250
9.4	14.1	16	2	18	.246
8.3	10.2	23.5	1.5	25	.273
8.4	12.9	18.5	0.5	19	.227
6.2	6.6	29	-19	10	.125
9.4	13.1	7.7	11.5	19	.234
9.8	18.2	6.5	11	17	.147
7.2	10.1	20	-10	10	.216
0	3.5	-	-	-	-

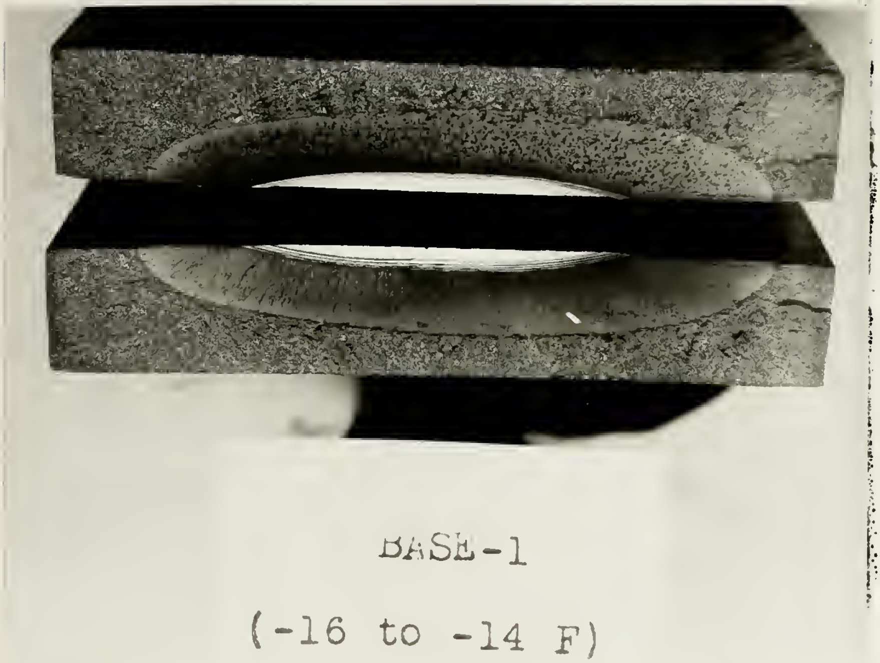

Figure IV-17. Photo, BASE-1.

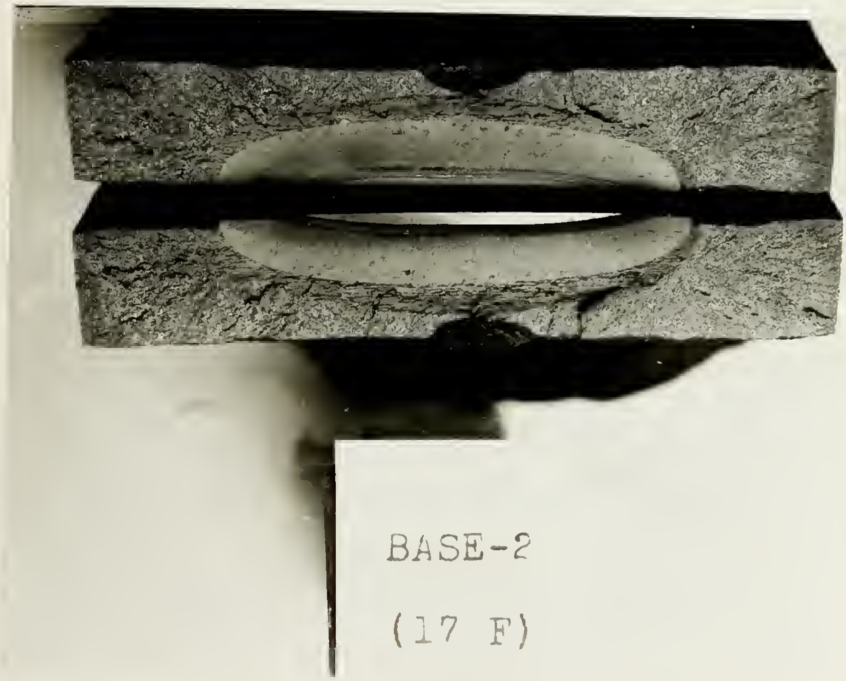

Figure IV-18. Photo, BASE-2.

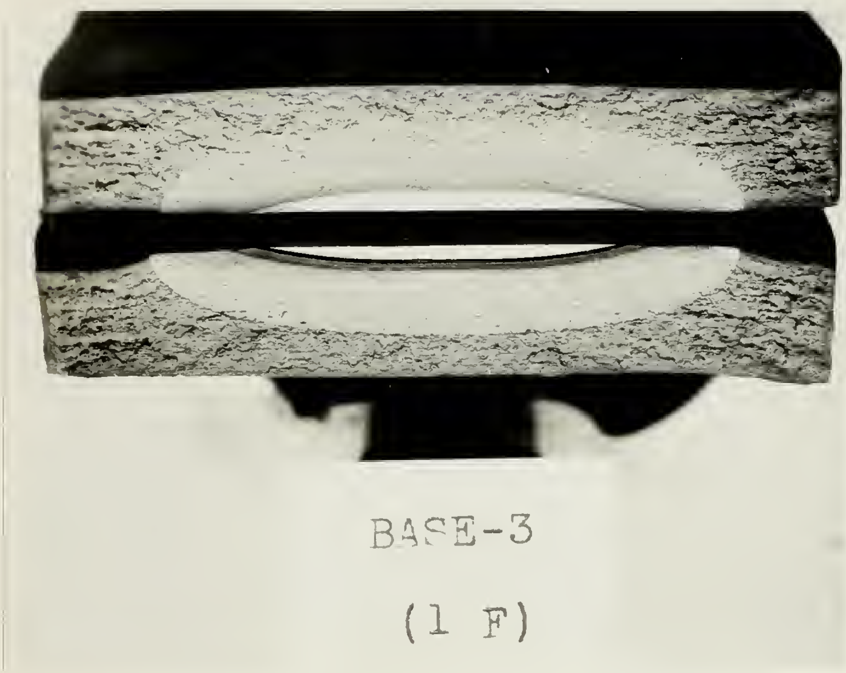

Figure IV-19. Photo, BASE-3.

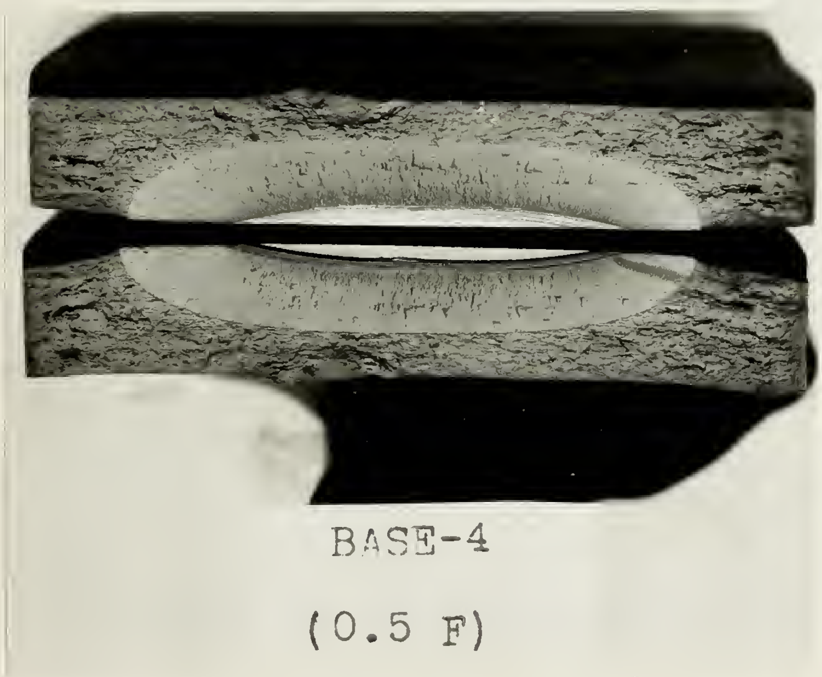

Figure IV-20. Photo, BASE-4.

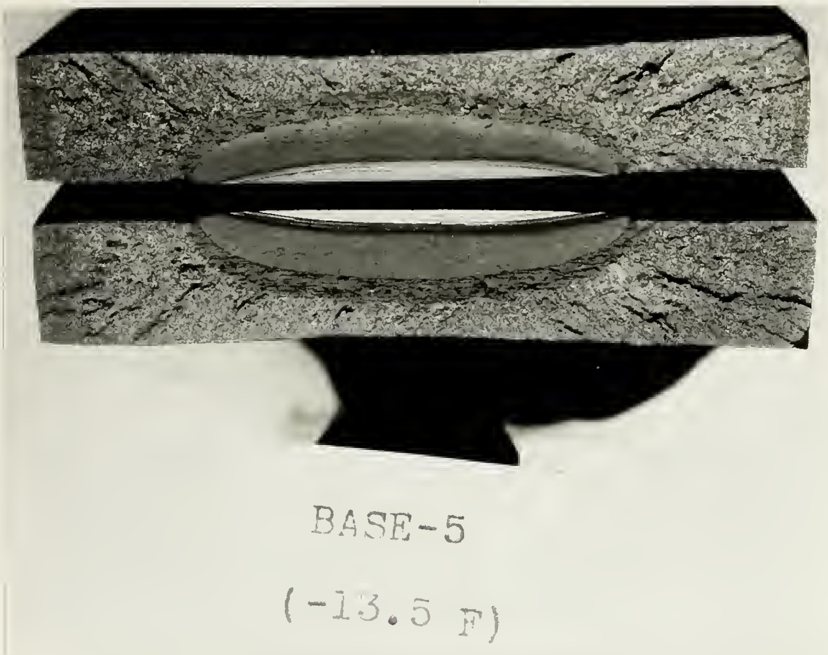

Figure IV-21. Photo, BASE-5.

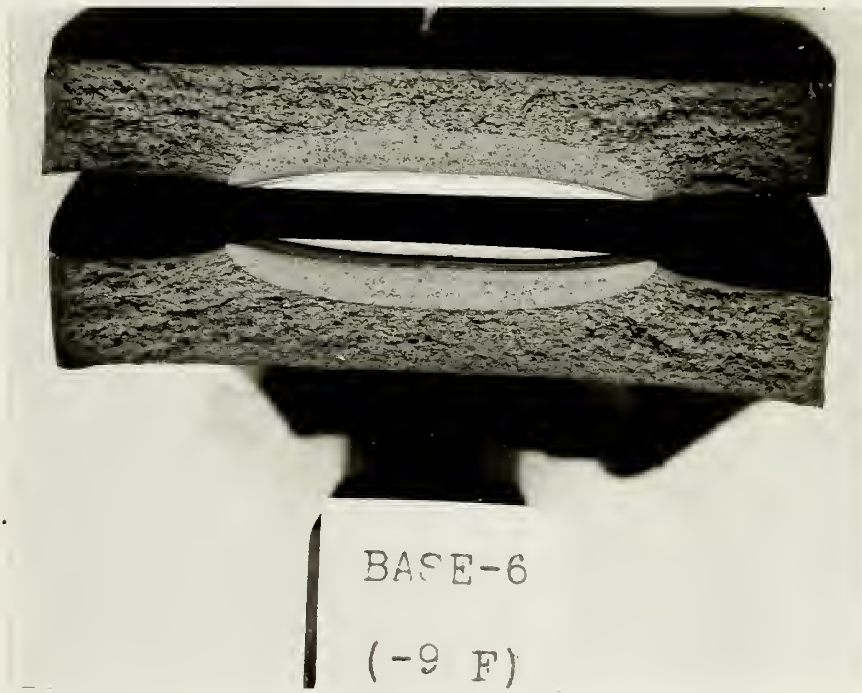

Figure IV-22. Photo, BASE-6.

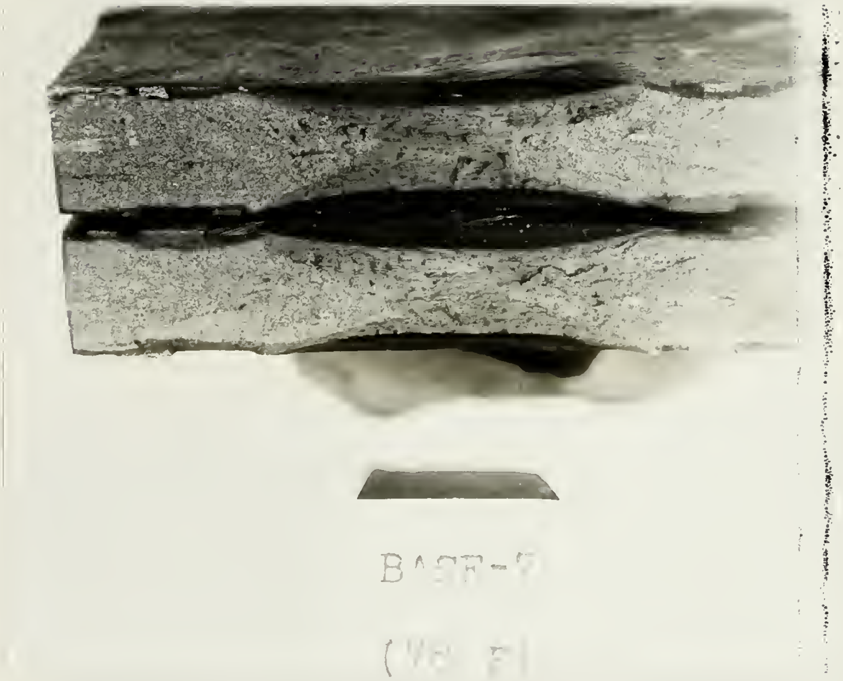

Figure IV-23. Photo, BASE-7.

Figure IV-24. Photo, HAZ-1.

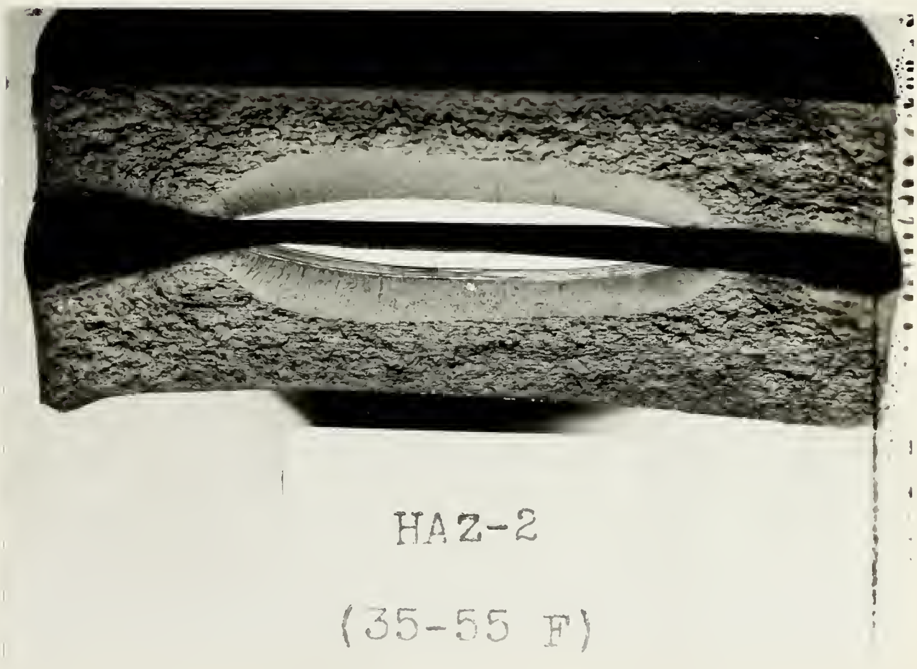

Figure IV-25. Photo, HAZ-2

HAZ-3

(45-55 F)

Figure IV-26. Photo, HAZ-3.

HAZ-4

(-30 to -15 F)

Figure IV-27. Photo, HAZ-4.

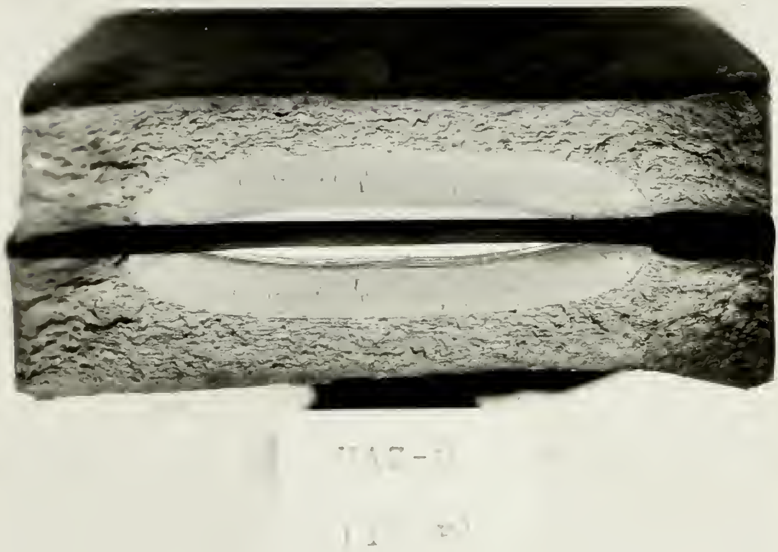

Figure IV-28. Photo, HAZ-5.

Figure IV-29. Photo, HAZ-6.

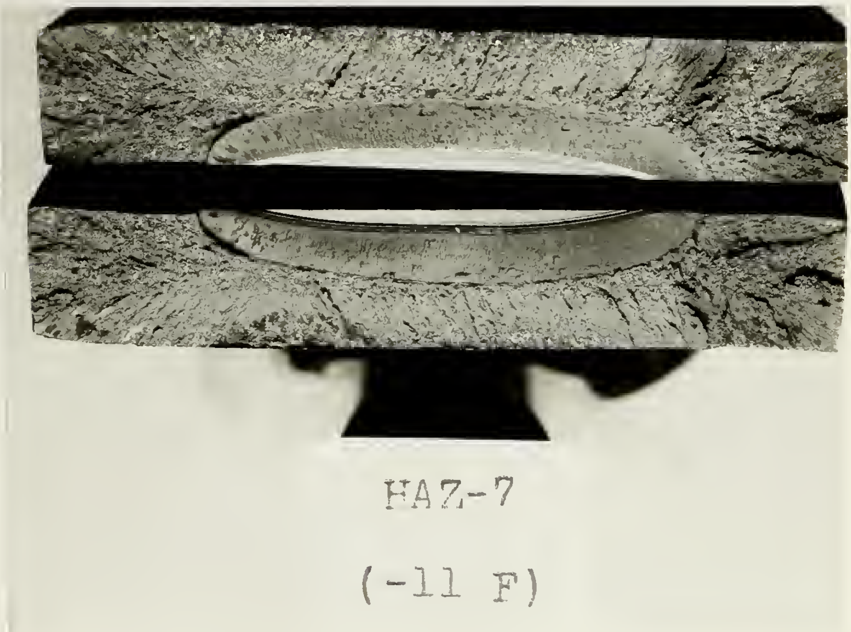

Figure IV-30. Photo, HAZ-7.

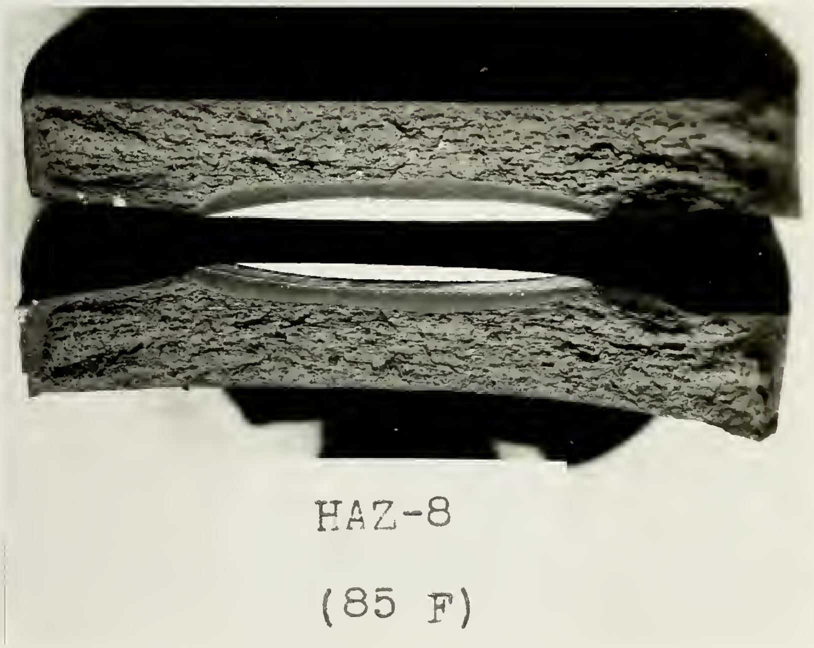

Figure IV-31. Photo, HAZ-8.

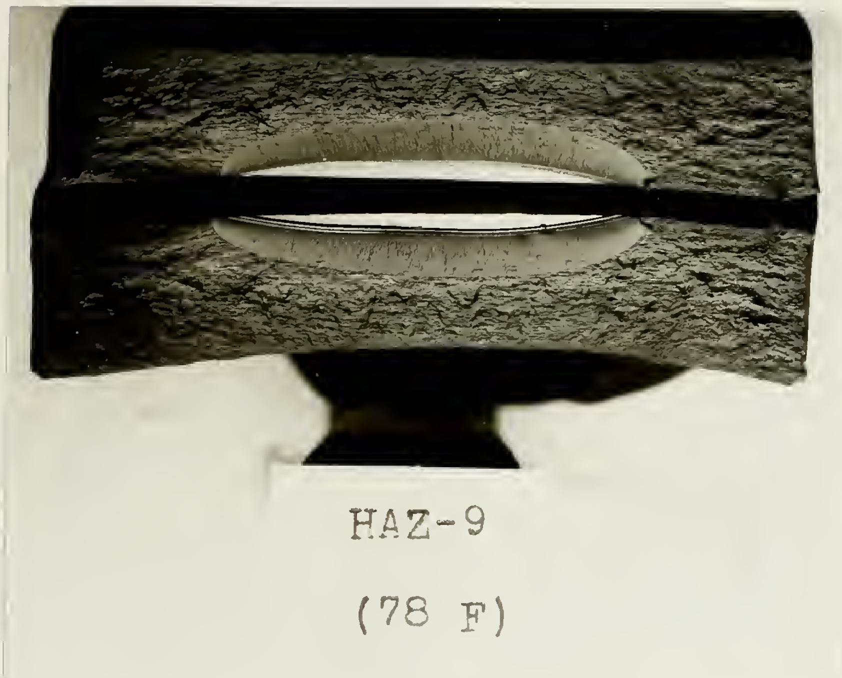

Figure IV-32. Photo, HAZ-9.

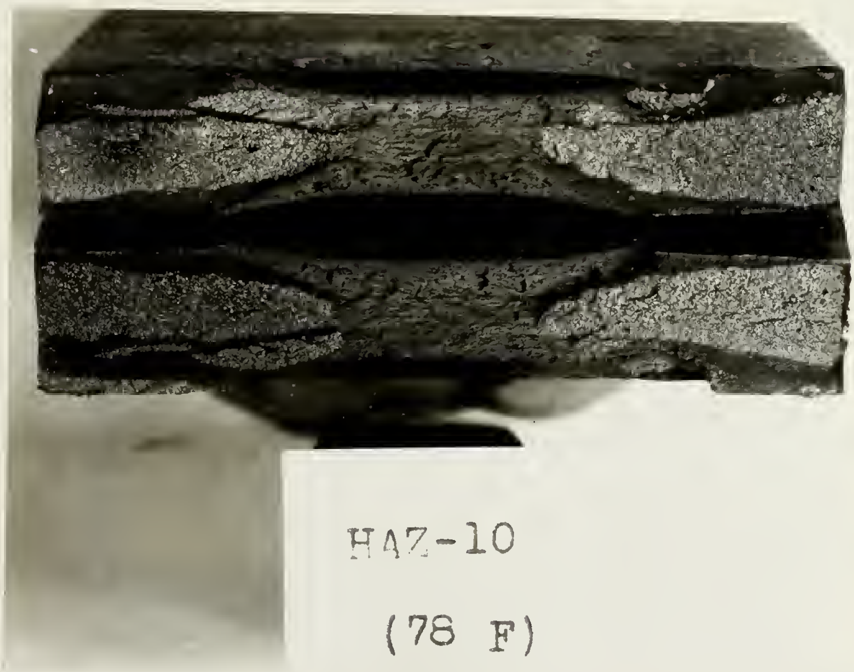

Figure IV-33. Photo, HAZ-10.

REFERENCES

1 Masubuchi, K., Martin, D.C., and Monroe, R.E. "An Interpretive Report on Weld Metal Notch Toughness", WRC Bulletin III, January 1966.

2 Marine Engineering Regulations, Subchapter F, CG-115, U.S. Coast Guard, Department of Transportation, Wash., D.C., June 1973.

3 "Guidelines for Explosion Bulge Testing of High Strength Q and T Steels, such as ASTM A-514 and A-517 for Structural Applications", Enclosure (2) of Merchant Marine Technical Note no. 4-68, U.S. Coast Guard, Department of Transportation, Wash., D.C.

4 Telephone Conversation with LCDR E.A. Henn, USCG, G-MMT-2, U.S. Coast Guard, Department of Transportation, Wash., D.C., 16 April 1975.

5 "Liquefied Flammable Gas Carriers Hull Steel Selection", CG Letter to Steel Companies, U.S. Coast Guard, Department of Transportation, Wash., D.C., 18 February 1972.

6 Conversation with CDR J.W. Kime, USCG, Chief, MMT-3, Governor's Island, N.Y., N.Y., 2 January 1975.

7 Conversation with LCDR E.A. Henn, USCG, G-MMT-2, U.S. Coast Guard, Department of Transportation, Wash., D.C., 21 January 1975.

8 "Structural Failure of the Tank Barge I.O.S. 3301 Involving the Motor Vessel Martha R. Ingram on 10 January 1972 without Loss of Life", Marine Casualty Report, no. USCG/NTSB - MAR - 74 - 1, performed and sponsored by the National Transportation Safety Board and U.S. Coast Guard, Wash., D.C., 28 December 1973.

9 Telephone Conversation with CDR J.W. Kime, USCG, Chief MMT-3, Governor's Island, N.Y., N.Y., 28 February 1975.

10 Rules for Building and Classing Steel Vessels, American Bureau of Shipping, N.Y., N.Y., 1972.

11 Telephone Conversation with Mr. Charles Null, Department of Metallurgy, American Bureau of Shipping, N.Y., N.Y., 8 April 1975.

12 Rules for Building and Classing Steel Vessels, Det Norske Veritas, 1974.

13 "Materials of Construction", Chapter VI, IMCO Gas Ship Code (rough draft).

14 Telephone Conversations with Mr. H. Sayre, Naval Ship Engineering Center, Hyatsville, Maryland, 8 - 9 April 1975.

15 "Welding and Brazing Procedure and Performance Qualification", MIL-STD-248C, Naval Ship Engineering Center, Department of the Navy, Hyattsville, Maryland, 12 October 1973.

16 "Steel Plate, Alloy, Structural, High Yield Strength (HY-80 and HY-100)", MIL-S-16216H (ships), Military Specification, Department of the Navy, 15 March 1972.

17 Conversation with Mr. P. Loftus, Welding Engineer, Quincy Shipbuilding Division of General Dynamics, Quincy, Mass., 17 December 1974.

18 Munse, W.H. "Brittle Fracture in Weldments", Ch. 8, vol. IV, Fracture, edited by Harold Liebwitz, Academic Press, N.Y., N.Y., 1969.

19 Kanazawa, T., Machida, S., Itoga, K., and Tsuchiya, H. "Study on the Brittle Fracture Initiation Based on the COD Concept" IIW Doc. X-665-72, Department of Naval Architecture, U. of Tokyo, Japan, April 1972.

20 Masubuchi, K. Materials for Ocean Engineering, MIT Press, Cambridge (1970), Chapter 12.

21 Pellini, W.S. "Evolution of Engineering Principles for Fracture-Safe Design of Steel Structures", NRL Report 6957, Naval Research Laboratory, Wash., D.C., 23 September 1969.

22 "Brittle Fracture Tests for Weld Metal", Concept Final Report of IIW Working Group 2912, Chairman: J.J. Nibbering, IIW Doc. X-754-74, 2912-196-74.

23 Pense, A.W., Stout, R.D., and Powell, D.G. "Development of a Weldment Fracture Toughness Test", a progress report to the Thermal and Mechanical Effects Subcommittee of the Pressure Vessel Research Committee's Fabrication Division, Lehigh University, Bethlehem, Pa., 1974.

24 Kihara, H. "Researches on Brittle Fracture Initiation of Welded Steel Structures in Japan". 17 July 1972.

25 Hall, W.J., Kihara, H., Soete, W., and Wells, A.A. Brittle Fracture of Welded Plate, Englewood Cliffs, N.J., Prentice-Hall, 1967, Chapter 9.

26 Pellini, W.S. "Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels", Welding Research Council Bulletin 130, May 1968.

27 Rolfe, S.T., Rhea, D.M., and Kuzmanavic, B.O., "Fracture Control Guidelines for Welded Steel Ship Hulls", SSC 244, Ship Structure Committee, Wash., D.C., 1974.

28 Loss, F.J. and Hawthorne, J.R. "Fracture Toughness Characterization of Shipbuilding Steels", SSC 248, Ship Structure Committee, Wash., D.C., 1975.

29 Judy. R.W., Puzak, P.P., and Lange, E.A. "Characterization of Fracture Toughness of 5 Ni-Cr-Mo-V Steel by Charpy V-Notch and Dynamic Tear Tests", NRL Report 6873, Naval Research Laboratory, Wash., D.C., 1 April 1969.

30 Puzak, P.P. and Lange, E.A. "Significance of Charpy-V Test Parameters as Criteria for Quenched and Tempered Steels", NRL Report 7483, Naval Research Laboratory, Wash., D.C., 10 October 1972.

31 Mryka, Dr inz. Jerzy "Resistance of Electroslag Welded Plates to Brittle Fracture", IIW Doc. X-755-74, International Institute of Welding, Gliwice, Poland, April 1974.

32 Banks, E. "Toughness Properties of HAZ Structures in Structural Steel", Welding Journal, vol. 53, no. 7, July 1974.

33 Watkins, B. "The Significance of the Heat Affected Zone in Fracture Initiation", Report from the Reactor Engineering and Materials Laboratory of the U.K. Atomic Energy Authority, May 1970.

34 Class notes, Course 13.16J "Fracture of Structural Materials", M.I.T., Fall 1974.

35 Dolby, R.E. and Saunders, G.G. "Sub-Critical HAZ Fracture Toughness of C : Mn Steels", Metal Construction and British Welding Journal, vol. 4, no. 5, May 1972.

36 Dolby, R.E. and Archer, G.L. "The Assessment of Heat Affected Zone Fracture Toughness", Conf. on Practical Applications of Fracture Mechanics to Pressure Vessel Technology, Inst. Mech. Eng., London, 1971.

37 Dolby, R.E. "Influence of Defect Orientation on HAZ Fracture Toughness Measurements", Metal Construction and British Welding Journal, July 1974.

38 Class notes, Course 13.12 "Marine Structures", M.I.T., Spring 1974.

39 McClintock, F.A. and Argon, A.S. Mechanical Behavior of Materials, Addison Wesley, Reading, Mass., 1966.

40 McClintock, F.A. "Local Criteria for Ductile Fracture", International Symposium on Fracture Mechanics, Kiruna, Sweden, 1967.

41 Matthews, W.T. "Plain Strain Fracture Toughness (K_{Ic}) Data Handbook for Metals" AMMRC MS 73-6, Army Materials and Mechanics Research Center, Watertown, Mass., December 1973.

42 McClintock, F.A. "Plasticity Aspects of Fracture", Ch. 2, vol. III, Fracture, edited by Harold Liebwitz, Academic Press, N.Y., N.Y., 1969.

43 "Standard Procedures for Preproduction Testing Materials by the Explosion Bulge Test", NAVSHIPS 0900-005-5000, Department of the Navy, November 1965.

44 "Mechanical Tests for Welded Joints", MIL-STD-418C Military Standard, Dept. of Defense, Wash., D.C., 15 June 1972.

45 "Metallurgy of Welding", lecture by M. Kutsuna at M.I.T., 13 March 1975.

46 Begley, J.A. and Landes, J.D. "The J-Integral as a Fracture Criterion", Fracture Toughness, Proceedings of the 1971 National Symposium on Fracture Mechanics, part 2, ASTM STP 514.

47 Begley, J.A. and Landes, J.D. "The Effect of Specimen Geometry on J_{Ic}", Fracture Toughness, Proceedings of the 1971 National Symposium on Fracture Mechanics, part 2, ASTM STP 514.

48 Bucci, R.J., Paris, P.C., Landes, J.D., and Rice, J.R. "J-Integral Estimation Procedures", Fracture Toughness, Proceedings of the 1971 National Symposium on Fracture Mechanics, part 2, ASTM STP 514.

49 Rice, J.R., Paris, P.C., Merkle, J.G. "Some Further Results of J-Integral Analysis and Estimates" Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536.

50 Shoemaker, A.K. and Rolfe, S.T. "The Static and Dynamic Low-Temperature Crack Toughness Performance of 7 Structural Steels", Engineering Fracture Mechanics, vol. 2, no. 4, June 1971.

51 McClintock, F.A. "Fracture Mechanics for Corrosion Fatigue", CORROSION FATIGUE: Chemistry, Mechanics, and Microstructure, NACE - 2, Natl. Acad. of Corrosion Engineers / Amer. Inst. of Metallurgical Engineers Conference, U. of Conn., Storrs, Conn., 1971.

52 Tada, H., Paris, P. and Irwin, G. The Stress Analysis of Cracks Handbook.

APPENDIX A

NOTCH TOUGHNESS TESTS

A.1 Charpy V-Notch Test

These tests are to be carried out in accordance with ASTM Specification E-23, "Notched Bar Impact Testing of Metallic Materials." The V-notch is the only one acceptable for Charpy testing. Acceptance criteria are specific impact energy values. A maximum allowable test temperature is specified along with this acceptance criterion usually.[2]

A.2 Drop Weight Test (DWT)

These tests are to be carried out in accordance with ASTM Specification E-208,"Conducting Drop Weight Tests to Determine Nil Ductility Transition Temperature." In testing a weldment, sub part 54.05 of CG-115 [2] requires the crack starter notch to be directly above the weld centerline. Further details of the DWT appear in reference [21].

A.3 Explosion Bulge Testing as Prescribed by the U.S. Navy

This test has been used extensively for determination of weldment performance in the Navy and elsewhere. According to NAVSHIPS 0900-005-5000 [43], "the test was demonstrated to be a simple and reliable method for determining the performance characteristics of service type weldments and represents the only feasible testing procedure by which

the heat affected zone of weldments and the performance of weld metal can be fully evaluated." The test is routinely required for quality assurance of HY-80/100 plate and weldments. Generally speaking, the test is used for higher strength steels as compared to mild steels [43].

Details of EB Testing

Before evaluating a weldment by the Explosion Bulge Test, the Navy requires certain information, specifically the detailed welding procedure and the other test data that is required to qualify the procedure. The Navy also requires that numerous mechanical test specimens be taken from prospective explosion bulge test welded plates (i.e. tensile specimens, longitudinal and transverse Charpy V specimens and bend specimens) to ensure compliance with the requirements of the respective base and weld metal procurement specifications. Prior to actual carrying out of the test, a screening method is required to single out inferior weldments which have no chance of surviving the explosion bulge test; this method is simply to use two explosion crack starter samples.[43]

The actual test weldment is required to be 2 inch thick material, 30 inches by 30 inches square. The explosion bulge test is conducted by applying repeated explosive shots; this delineates those regions of the weldment which undergo

fracture initiation and propagation. These fracture paths are one of the major parameters to be observed in the test (with a sketch or photograph). The other major parameter is the reduction in plate thickness in the absence of cracking. This shall be noted after each shot of explosive, until 16% reduction occurs, at which time no cracking outside the bulged region indicates acceptance. Specimen temperature is to be strictly controlled for each shot of explosive. A minimum of four test specimens must show acceptable performance. [43]

A.4 Dynamic Tear Test

The DTT was developed at the Naval Research Laboratory in 1962. It's advantage over the Charpy test is its capability to not only evaluate transition behavior more effectively in all steels, but to more accurately evaluate the properties of steels which don't have large increases in ductility at their transition temperatures. These steels are the high strength and ultra-high strength steels plus also those intermediate strength steels that feature definite weak directions.[21]

The DTT measures impact energy just as the Charpy test does. However its geometry is considerably different (figure A.1). The specimen has more material ahead of the notch. The purpose of this is to create enough constraint

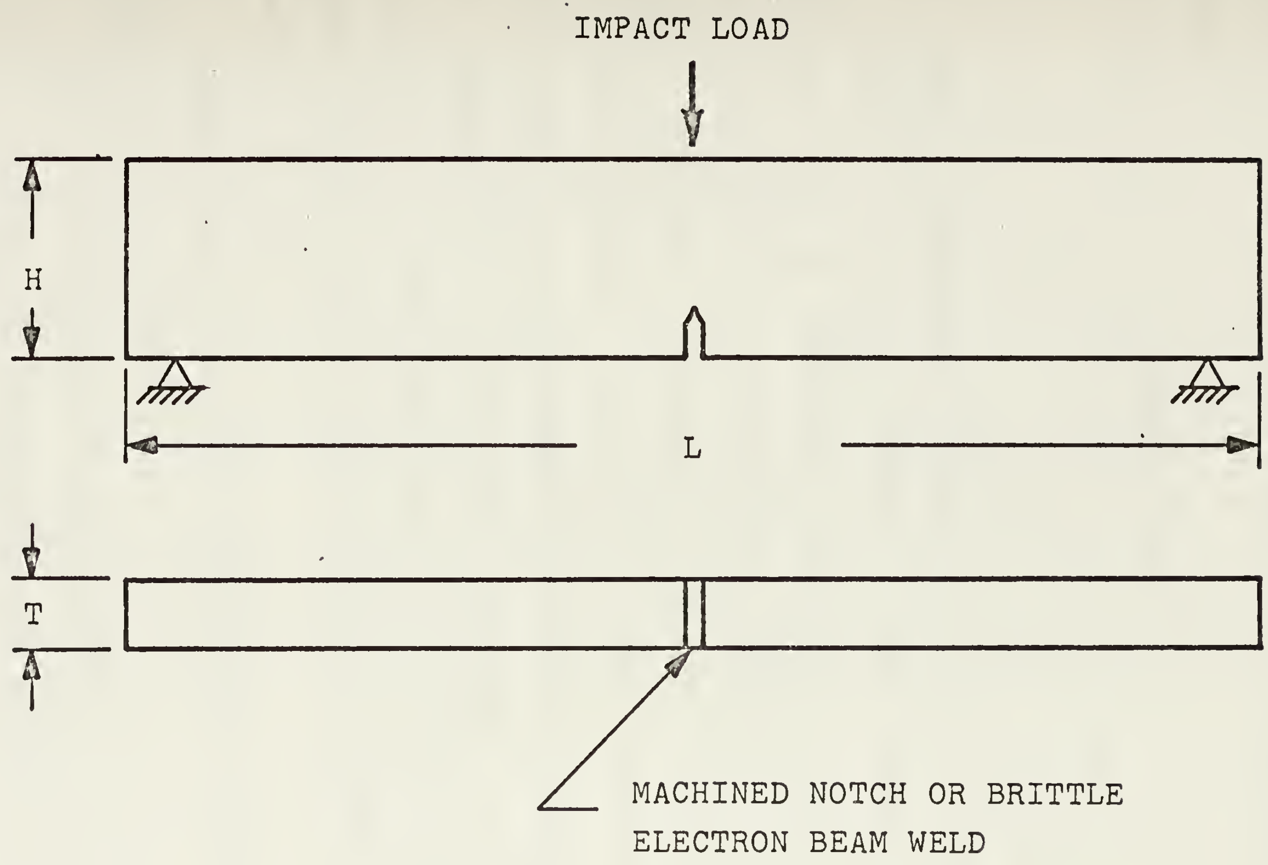

Figure A-1. Configuration of Dynamic Tear Test (DTT) specimen.

so that a sharp crack can easily get started. This has the effect of subjecting the specimen to a sharp running crack and thus giving some indication of the material's resistance to same.

There are two standard sizes:

T = 5/8 in.: L = 7 in., H = 1.625 in.

T = 1.0 in.: L = 18 in., H = 4.75 in.

A.5 Impact Testing as Prescribed by the U.S. Navy

Either the Charpy V-notch or the dynamic tear test (DTT) are used by the Navy, depending on which one a particular material specification calls for [44]. Impact energy values are specified for the base material and for the weld electrode. However for weld procedure qualification impact tests, the assessment criteria for weld metal is the energy value for the weld electrode, not the base plate. It should be noted that there is no requirement for HAZ impact tests; just the weld metal is required to be impact tested. [15 , 44]

Impact tests are only required for certain situations. These are as follows [15]:

a) for automatic, semi-automatic, and machine welding process in structural applications of "S-1" material in plate*

*C-Si steel (Y.S. = 30-38 k.s.i.); type 1 and 2 grade HT steel (Y.S. = 42-50 k.s.i.); and grade N steel (Y.S. = 42-70 k.s.i.)

b) for "dissimilar metal" (as defined in reference [15]) welds when both base materials and weld electrode all have impact energy requirements

c) for cases where both the base metal and weld metal have impact requirements

In all these situations, however, impact testing is only required if the material is over 3/4 in. thick.[15]

A.6 Crack Opening Displacement (C.O.D.) Test

This test uses a small notched specimen, generally, subject to slow loading. The opening of the notch during loading is measured. A critical value is gotten for a given temperature when the piece fractures. Transition temperature curves are plotted for these critical COD's. [19, 22]

A.7 Niblink Test

This test has been used by the International Institute of Welding [22]. It uses a small notched specimen, as the COD test does. However, the difference lies in limiting the crack opening to a specific value for all specimens. The purpose of doing this is to keep "the same plastic reserve for each steel" [22] type tested, regardless of yield strength. [22]

Minor impact blows are used to deflect the specimen to the above-mentioned limit. More than one blow is

necessary usually. If the specimen does not fracture prior to reaching the limit, it is considered to be above its transition temperature. [22]

APPENDIX B

STEEL CATEGORIES FOR USCG REQUIREMENTS

B.1 Ferritic Steels [2] (less than 0°F)

Carbon and low alloy steels are covered in this category. Materials shall conform to a specification given in table UCS-23 of the ASME Code and a number of additionally imposed Coast Guard requirements. For minimum service temperatures above -70°F these additional requirements are as follows: fine grain practice, normalized (other heat treatments may be considered), austenitic grain size of 5 or finer, maximum Carbon content between 0.12% and 0.20% and Manganese range between 0.90% and 1.65% depending on the minimum service temperature. Silicon range is 0.10% - 0.35%. Maximum allowable phosphorous and sulfur is 0.04%. Mechanical properties are limited as follows:

Ultimate strength:	58,000 - 85,000 psi
Yield strength:	minimum 35,000 psi maximum 80% ultimate strength
Elongation (min.):	20% in 8 inches, or 24% in 2 inches, or 22% in 5.65 A, where A is the test specimen cross sectional area

For minimum service temperature below -70 F the additional CG requirements are considerably different.

The steel must be normalized, low carbon, and fine grain as before; but it must also be fully killed and be a Nickel alloy type. These steels include the following:

A203, $2\frac{1}{4}\%$ Ni normalized

A203, $3\frac{1}{2}\%$ Ni normalized

5% Ni normalized

From these ferritic steels (both < 0°F and < -70°F) average Charpy energy values were gotten. These values are the official numbers which comprise the Coast Guard toughness test acceptance criteria for < 0°F and for < -70°F (subpart 54.05 of CG-115) [2]. These numbers were gotten by running Charpy tests on these materials near the NDT temperature (determined from the drop weight test).

B.2 <u>High Alloy Steels [2]</u>(less than 0° F)

This category of materials covers a range of different low temperature designations, for stainless steels, primarily. The types of steels that are included are specifically listed in the ASME Code, Section VIII under UHA-51, which lists three categories. The first one is for service temperatures below -425 F and includes Types 304, 304L and 347. The second is for materials operating at service temperatures below 0 F and includes certain stainless types, those "in casting form" (ref. ASME Code),

and those "in the form of deposited weld metal" (ref. ASME Code). The third category of steels is for all values of service temperature. They are: Types 309, 310, 316, 309Cb, 310Cb and 316Cb.

If any of these steels had a Charpy specification, then the weldment would have to pass the same Charpy acceptance criteria. But, generally speaking, these stainless steels will not have Charpy specifications. In fact, the CG rules prefer using the DWT instead of the Charpy test for austenitic stainless steels.

B.3 Ferritic Steels with Properties Enhanced by Heat Treatment [2] (less than 0°F)

This category covers specific materials but is limited to five 9% Ni steels (A-333 grade 8; A-334 grade 8; A-353 double normalized and tempered; A-522, quenched and tempered, forging; A-553 quenched and tempered). The lowest allowable temperature is -320°F.

Charpy testing of these materials is slightly different than for the others. Instead of being required to exceed a certain minimum Charpy energy value, the acceptance criteria give a minimum value of lateral expansion opposite the notch. This lateral expansion is used the same way that the absorbed energy value is used in the other cases. That is, traversing the HAZ and the weld is required for

weld procedure qualification (Subsection II.A.4). For information only, values of Charpy energy and fracture appearance are also required to be recorded.

B.4 Quenched and Tempered Steels [2]

These steels are those other than any quenched and tempered 9% Ni steels which were covered previously. Here, special considerations are given to the welding as opposed to the actual plate specification. Subchapter F reports that the Coast Guard "may prescribe special testing to assure that the welding procedure produces weldments which are not prone to low energy fracture through the HAZ." [2] The most common "special testing" is the explosion bulge test [3]. This follows closely with the theory (Subsection III.A.3) that Charpy tests are invalid for higher strength steels. It also follows the Navy's procedure for HY-80/100 weldment quality assurance. The explosion bulge test, as prescribed by the Navy, is described in Appendix A.3. Coast Guard use of the test is similar to that of the Navy [2].

B.5 Hull Steels (for Liquefied Petroleum Gas Carriers)[5]

The growth of cold service applications has led the Coast Guard to requirements for ship's hull steel, in addition to cold pressure vessel, and primary and secondary barrier steel (which is what is specifically addressed

in CG-115) [2]. Review of hull steel is only required for liquefied flammable gas carriers if mean temperature of the steel (as calculated by surrounding temperatures) is less than 0°F. This is the same cut-off temperature as for pressure vessel and semi-pressure vessel tanks (an exception to this is in steels for primary and secondary barriers to pressure vessels — above 0°F but below 32°F the only requirement is to use certain steels: ABS grade CS, CN, C or equivalent).

Rules for hull steel are more lenient than for pressure vessels (and primary and secondary barriers). Between 0°F and -10°F Charpy testing is required but only for weld procedure qualification (steel selection is limited to ABS grade CN, CS or equivalent).

Below -10°F but greater than -30°F the steel must meet the requirements of Subchapter F, which are the same as for the pressure vessel steels. However, special consideration may be given to some classification society grades. Charpy tests are required for weld procedure qualification for this temperature range.

For operating temperatures below -30°F, the steel also shall meet the requirements of Subchapter F (CG-115) [2].

So, in effect, for all hull steel below 0°F the weld procedure shall be qualified with Charpy tests, including HAZ specimens.

APPENDIX C

GENERAL BACKGROUND

C.1. HEAT AFFECTED ZONE CRACKS [45]

HAZ cracks are usually formed from either hot cracking or cold cracking. The following outline [45] illustrates the mechanisms and types of crack for each.

HOT CRACKING

a) Segregation cracking (T_c^* > solidus)

Type of HAZ crack: liquefaction cracking

b) Low ductility cracking

($0.5\ T_m^* < T_c <$ solidus)

Type of HAZ crack: low ductility cracking (caused by lamellar tearing)

COLD CRACKING

a) Types of cold HAZ cracks: toe crack

underbead crack

root crack

---

* T_c = crack initiation temperature; T_m = melting temperature.

C.2. J-INTEGRAL (J_{Ic})

The J-integral is a criterion for quantitative evaluation of fracture toughness where plastic flow is beginning to affect the overall force-deflection curve of the structure. It has been related to the idea of K_{Ic}. One major benefit of attaining a critical value of J_{Ic} versus K_{Ic} is that the former is suitable for a larger degree of plasticity at the crack tip than the latter.

The other major benefit of the J-integral is that when the Hutchinson-Rice-Rosengren (HRR) singularity dominates the stress and strain field around a crack tip, the J-integral specifies the magnitude of the singularity and hence, fracture.

It should be noted that the J-integral may not apply when fully plastic behavior occurs. The reason is that the HRR singularity gets distorted from the effects at the free boundary as well as the blunting effects at the crack tip.*

Detailed explanations and applications of the J-integral are given by Begley and Landes [46, 47], 1971, Bucci et al. [48], 1972, and Rice, Paris and

---

*Blunting effects are encountered in both cases (brittle and fully plastic), actually; i.e. the HRR singularity does not hold right <u>at</u> the crack tip, for this reason.

Merkle [49], 1973.

C.3. CRACK OPENING ANGLE (COA) AS A MEASURE OF DUCTILITY

COA is defined as the angle between two fracture surfaces as shown in Fig. C-1. It can be used as an indication of the amount of ductility present during fracture in fully plastic parts. For brittle fracture, this angle is nearly zero.

The specific relation of this angle to ductility, neglecting elastic strain, is as follows:

$$\gamma = \frac{2}{1 + \dfrac{1}{\tan(\frac{COA}{2})}} \qquad \text{(C-1)}$$

where γ = shear strain.

The larger the shear strain, the greater the ductility. The minimum shear strain for plastic behavior is the yield strain,

$$\gamma_{ys} = \frac{\sigma_{ys}}{E} = \frac{40,000}{30,000,000} = 0.00167 \; . \qquad \text{(C-2)}$$

The crack opening angle for this shear strain is $0.1°$. Any angle greater than this value indicates the presence of some degree of plasticity - the greater the angle, the greater the degree of plasticity [40].

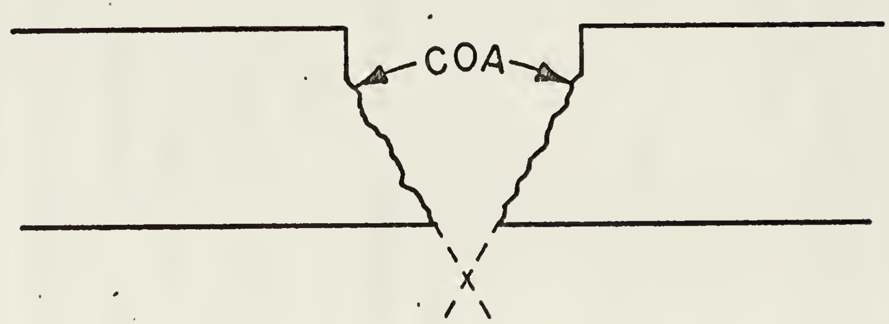

Figure C-1. Definition of crack opening angle (COA).

C.4. STRAIN RATE CALCULATIONS

The effects of increased loading rates, and the resultant increased strain rate, is known to raise the transition temperature of metals. This has been shown many times experimentally, reference [50] being only one example. The effects of increased strain rate can be calculated by the "velocity-modified temperature" [39] for plastic deformation:

$$T_m = T(1 - \alpha \ln (\dot{\varepsilon}/\dot{\varepsilon}_o) \qquad \text{(C-3)}$$

where $\alpha = 0.018$.

Using this relation, the numbers in Table C-1 indicate the expected increase in transition temperature for a given increase in strain rate.

The velocity-modified temperature underestimates the observed results by Shoemaker and Rolfe [50], 1971. They observed an 80°F increase in transition temperature* for strain rate increased by a factor of 2×10^3 . For this same rate increase, the above relation predicts an increase of 36°F . Thus it would seem that one might expect larger, if not the same, increases in transition temperature than

*This transition temperature was that at which plastic zone size for K_{Ic} tests became too large.

TABLE C-1.

INCREASED TRANSITION TEMPERATURE

FOR INCREASED STRAIN RATE

$\dot{\varepsilon}/\dot{\varepsilon}_o$	INCREASED TRANSITION TEMPERATURE (as calculated by Equation C-3) °F
2	5.7
4	11.5
10	19.1
30	28.2
100	38.1
1000	57.2

those predicted by Eq. C-3. This is important because this relation predicts significant variations in transition temperatures for the test results (note from Table IV-6 that load rates varied between specimens, excluding HAZ-8 and HAZ-9, by as much as 30:1 which could cause a 28°F rise in transition temperature). But it is important to note that at the transition temperatures of both HAZ and base metal test strips, the load rates were all the same order of magnitude (see Table IV-6, piece numbers BASE-5, 6 and HAZ-6, 7). The average of these four is 92.25 lb/sec (61.5 psi/sec).

SHIP LOADING

Assuming a design stress of 35,000 psi , loading rates of 10,000 psi/sec and 20,000 psi/sec correspond to loading to design stress in 3.5 sec. and 1.4 sec. respectively. These are considered to be very realistic rates of loading for a ship in a storm.

APPENDIX D

EXPERIMENTAL DETAILS

D.1. TEST STRIP

The strips (Fig. IV-1) used for testing were cut from half inch welded plate. The width was 3 inches, a limit imposed by the test machines grips. The long 24 inch length was required so that adequate portions of this length could be taken up by the tension machine grips (Fig. IV-1).

The pieces were cut by a shearing machine, and the edges were milled to remove the highly strained material caused by shearing. Most specimens were not straight. They were bent slightly, due either to welding stresses or the shear cutting.

NOTCH DETAILS

Figure D-1 illustrates notch cross-section dimensions. The sharp point was required to facilitate growing fatigue cracks. Attaining this point was done by sharpening a circular cutter (saw blade) to 30 degrees of bevel. Strength limitations of the blade called for using a thicker (3/64 inch) one than desired.

Figure IV-2 illustrates the straight-fronted notch shape. The blade diameter used in cutting the notch was 4 inches, again larger than desired. But the reason a

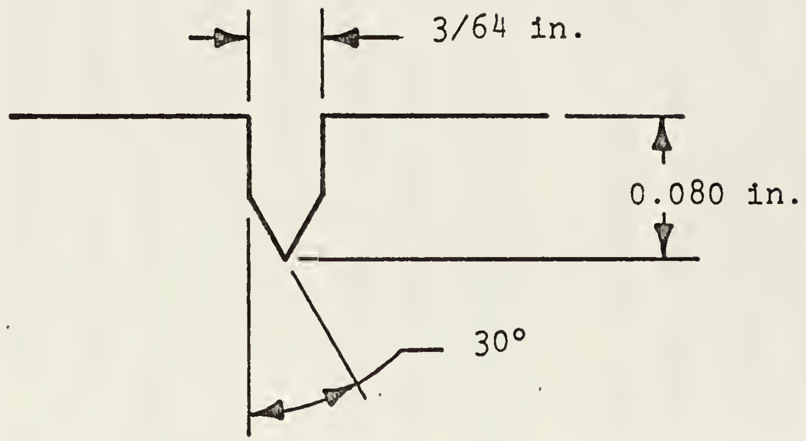

Figure D-1. Notch cross-section.

larger diameter blade was used is that some milling machines would not allow a smaller blade to penetrate the specimen due to their mountings getting in the way.

D.2. GROWING FATIGUE CRACKS

An SFIU Sontag fatigue machine, located at the Army Materials and Mechanics Research Center in Watertown, Massachusetts, was used to grow fatigue cracks in the test plates. This machine operates at 1800 cycles per minute.

Ultimately, fatigue cracks were grown with a tensile pre-load of 2800 in-lb and cycled at ± 3500 in-lb; this resulted in cycle limits of 6300 in-lb in tension* and -700 in-lb in compression*.

Growing fatigue cracks for these test plates was largely a matter of experience. No quantitative means were used to develop a method. Crack growth was monitored to a limited extent with a strobe light. But there was simply no way to know exactly how deep a given crack had propagated. However, estimates could be made based on the extension of the crack over the surface of the test strip.

One source of inconsistency was the bending which most test strips had undergone from welding and/or shearing

*"Tension" or "compression" is used here in relation to the notched surface.

(Appendix D.1). Different amounts of pre-load were required for each of these.

For the pieces with notches in the weld, fatigue cracks could not be grown. This was due to failure in the unnotched HAZ for all cases. The same problem also occurred for 50% deeper notches in the weld metal (i.e. 0.12 in.). Some calculations will illustrate quantitatively why this was so.

CALCULATIONS

The rate of fatigue crack growth can be expressed as follows [51]:

$$da/dN \propto \Delta CTD_1 \approx 4\ \Delta r_1 \frac{2Y}{E} = \frac{2\Delta k_1^2}{2YE} \qquad \text{(D-1)}$$

where

da/dN = crack growth/cycle

CTD_1 = crack tip opening

r = plastic zone size

Y = material yield strength

E = modulus of elasticity

k_1 = stress intensity factor = $\frac{k_1}{\sqrt{\pi}}$

Assuming a constant E, the crack growth rate of the weld can be compared to that of the HAZ in the following proportionality:

$$\frac{(da/dN)_{haz}}{(da/dN)_{weld}} = \left(\frac{k_{haz}}{k_{weld}}\right)^2 \frac{Y_{weld}}{Y_{haz}} \tag{D-2}$$

Using the single edge-notch [52] geometry (Fig. D-2) as an approximation to test strip geometry,

$$k = \sigma \sqrt{a}\, F(a/b) \tag{D-3}$$

where σ = stress = $\frac{6M}{b^2}$

M = applied moment (constant)

$\left.\begin{array}{l} a = \text{crack depth} \\ b = \text{thickness} \end{array}\right\}$ Fig. D-2

thus

$$k = 6M \frac{\sqrt{a}\, F(a/b)}{b^2} \tag{D-4}$$

For the HAZ, $a = 0.08$ in., $b = 0.5$ in., and $F(a/b) = 0.806$ [52] . Thus, $k_{haz} = 0.9119\ (6M)$.

For the weld, $a = 0.08$ in., $b = 0.625$ in., and $F(a/b) = 0.8508$ [52] . Thus, $k_{weld} = 0.6160\ (6M)$.

For the deeper weld notch, $a = 0.12$ in., $b = 0.625$ in., and $F(a/b) = 0.7612$ [52] . Thus $k_{deep\ weld} = 0.6750\ (6M)$.

Before entering Eq. D-2, yield strength must be obtained. Because this was not known for the HAZ, ultimate tensile strength, as determined from the hardness measurements will be used instead. Taking $(R_B)_{weld} = 88.7$ and

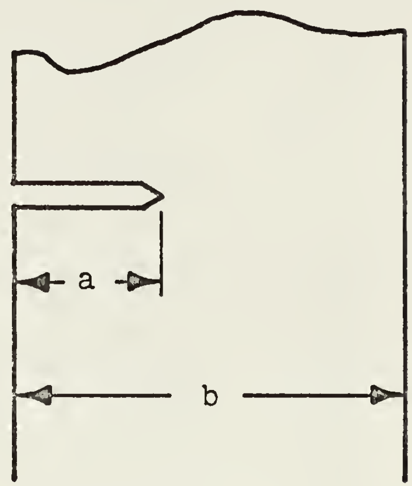

Figure D-2. Single edge-notch geometry used to approximate test strip configuration for fatigue calculations.

$(R_B)_{haz} = 83.3$ (Table IV-5) and soving the following relation for B (Brinell hardness = UTS) [39],

$$R_B = 130 - \frac{9000}{B} \tag{D-5}$$

$$B = \frac{9000}{130 - R_B} \tag{D-6}$$

From Eq. D-6,

$$B_{weld} = 217.9 \text{ kg/mm}^2$$

$$B_{haz} = 192.7 \text{ kg/mm}^2$$

Using the k's and B's above in Eq. D-2, it can be seen exactly how much lower the crack growth rate in the weld actually was, even for the deeper notch:

$$\frac{(da/dN)_{haz}}{(da/dN)_{weld}} = \left(\frac{.9119}{.6160}\right)^2 \frac{217.9}{192.7}$$

$$= 2.48$$

(crack growth in weld is 40.3% of HAZ)

$$\frac{(da/dN)_{haz}}{(da/dN)_{deep\ weld}} = \left(\frac{.9119}{.6750} \right)^2 \frac{217.9}{192.7}$$

$$= 2.06$$

(crack growth in weld is

48.5% of HAZ)

These calculations substantiate the inability to grow fatigue cracks in the weld.

D.3. TEMPERATURE MEASUREMENT

A welded thermocouple, made from 28 gage Chromel-Alumel wire was used to monitor temperature of most test strips. The thermocouple was inserted into a hole (of slightly larger diameter) drilled to approximately one third of the test strip thickness (1/6 in.).

The entire 10 in. area of the test strip between the grips was insulated with asbestos ribbon to minimize speed of heating after each was removed from dry ice.

The accuracy of temperature measurement is estimated to be roughly $\pm$ 2°F . Temperatures noted were probably a bit on the higher side due to incomplete contact of thermocouple with steel; but this effect was consistent for all test strips.

Thesis
M3415
Marcolini
Notch toughness requirements for welded plate, and a proposed test.